Environmentally relevant future topics

FROM LAB-GROWN FUTURE TO THE MARITIME ALGAE INDUSTRY AND THE INTERNET OF THE FUTURE

Results of the third horizon scanning cycle for the Environment Department

For people & the environment

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Wörlitzer Platz 1
06844 Dessau-Rosslau
Tel: +49 340-2103-0
Fax: +49 340-2103-2285
buergerservice@uba.de
Website: www.umweltbundesamt.de/en

Authors:
Stephan Richter, Tobias Hungerland, Nikolas Hubel,
Katharina Dassel, Lia Meissner, Mona Hille, Désirée Tillack
Institute for Innovation and Technology (iit)
at VDI/VDE Innovation + Technik GmbH, Berlin

Gideon Hussels, Walter Kahlenborn, Anika Conrad,
Jan Christian Polanía Giese, Helin Aras
(adelphi consult GmbH, Berlin)

Editorial office:
Subject area 1.1
Sylvia Veenhoff

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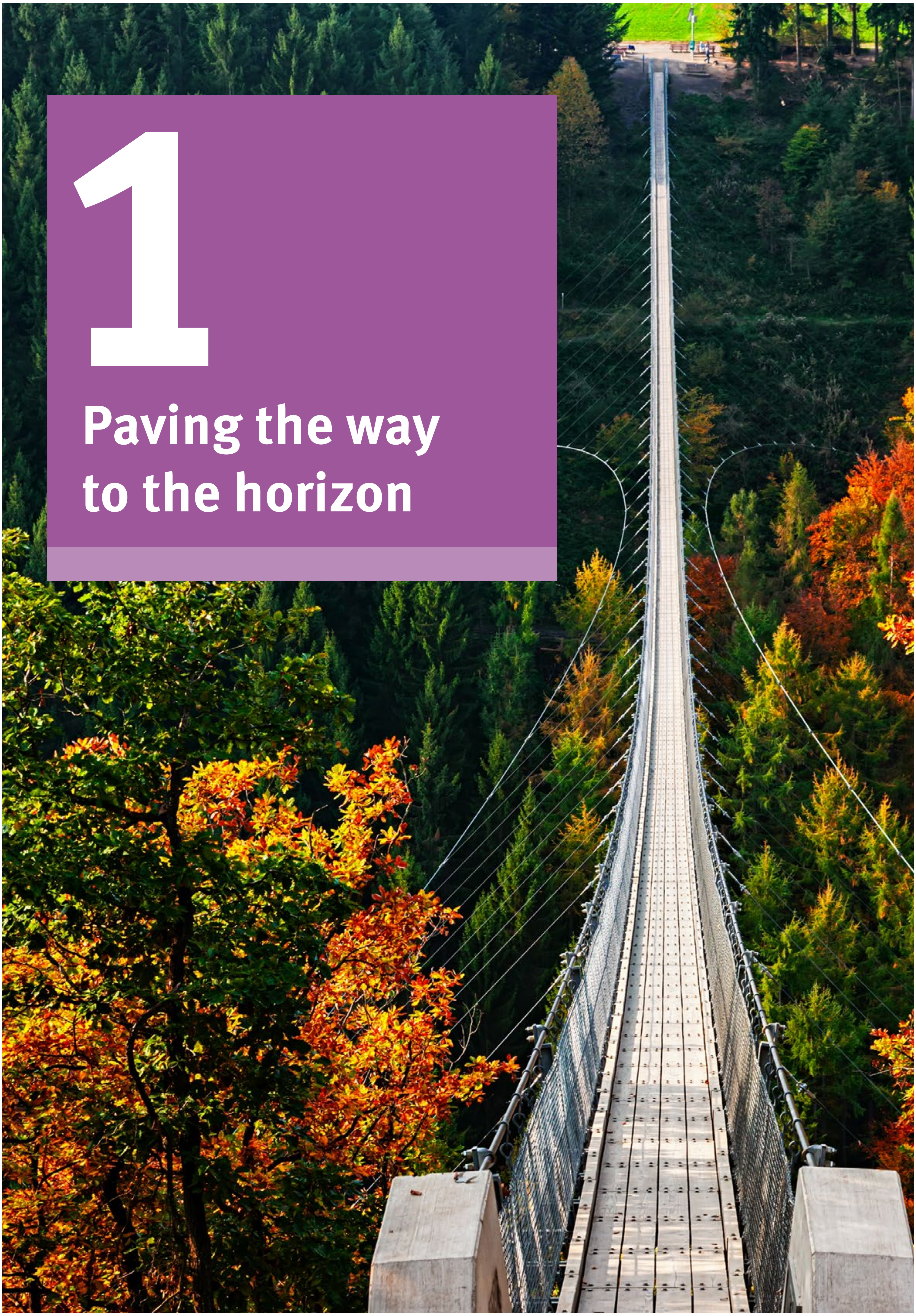


1 Introduction: Paving the way to the horizon

1.1 Horizon scanning for the Environment Department amidst multiple ongoing challenges

Far-reaching events are casting a shadow over our social achievements: the Covid-19 pandemic is having a lasting effect, Russia's war of aggression against Ukraine has ended a long period of peace and growth in Europe and acts of war in the Middle East are having an impact which goes right into the heart of our cities and societies. These highly topical events, also known as the "polycrisis", partly overshadow the long-term global challenges caused by the triple crisis of climate change, biodiversity loss and environmental pollution.

However, our society cannot afford to lose sight of the triple crisis, as its consequences are far more serious than the effects of the current challenges. Society will suffer from the triple crisis from both an economic and a health perspective.

Climate-related extreme events have led to economic losses of an estimated EUR 650 billion in the European Union over the past four decades, including more than EUR 100 billion in 2021 and 2022 alone (European Environment Agency 2023; European Environment Agency 2024). German greenhouse gas and air pollutant emissions in the road transport, electricity and heat generation sectors in 2021 caused costs of at least EUR 241 billion (Federal Environment Agency (UBA) 2024). The existing funding gap to restore biodiversity by 2030 is estimated at USD 711 billion per year (Allianz Trade 2023). The later and the more hesitantly environmental risks are mitigated through suitable measures, the more the costs threaten to rise.

Health consequences, such as cardiovascular events caused by increasing heatwaves or deaths caused by overheating, will affect a significant proportion of the world's population in the future. Between one and three billion people could live in areas where the average annual temperature is 29° C (Hungerland et al. 2023; p. 23ff.). It is already apparent that around 220,000 people across Europe have died as a result of extreme weather events since 1980 (European Environment Agency 2023). In the future, these numbers are likely to rise significantly and cause further effects, such as increasing migration movements.

Although there are international goals and resolutions for more environmental protection and the preservation of biodiversity, as well as numerous measures to combat climate change and adapt to its consequences, their implementation is proving difficult: for example, the United Nations (UN) has not yet achieved its sustainability goals. The challenges appear to be too great, diverse and complex to be overcome in the short term with isolated measures.

This is why continuous strategic foresight is becoming increasingly important for the Environment Department: our highly complex, dynamic world is not only characterised by acute and far-reaching events such as the polycrisis mentioned above, but also by overarching, far-reaching developments that are much more threatening in their effects – the so-called triple crisis. Numerous interactions can be identified: while some developments in the context of the Covid-19 pandemic had positive effects on the environment – such as the decline in global air traffic – numerous disruptive events – such as the escalation of violence in the Middle East – are now leading to numerous new developments with potential environmental impacts. This is where horizon scanning comes in, in which an attempt is made to generate orientation knowledge for the Environment Department at an early stage and to identify relevant future topics. This should enable the Environment Department to formulate options for action.

Horizon scanning is an instrument for the strategic early detection of socio-economic, technological, political and ecological changes (Behrendt et al. 2015). The purpose of horizon scanning is to identify weak signals, emerging issues and developments and trends (Cuhls et al. 2015). The primary aim of horizon scanning for the Environment Department is to identify emerging developments with starting points for environmentally relevant measures for an anticipatory environmental policy. Such an environmental policy should help to exploit opportunities for sustainability and environmental protection at an early stage, but also to minimise potential risks to the environment and damage or hazards due to problems in the implementation of environmental and sustainability policy measures. In this way, an anticipatory environmental policy can help to make society more resistant to challenges and more resilient overall.

Horizon scanning does not take place in isolation from its context. The identified topics and their development are shaped by the social, political, technological, economic and ecological environment. As previously mentioned, the current trend environment is dominated by a highly dynamic and turbulent polycrisis, while an overarching triple crisis is influencing current developments in the background.

Some of the future issues identified in this horizon scanning cycle therefore represent overarching challenges with only indirect links to environmental policy. These include, for example, the topics "Democracy in danger" (see chapter 2.4), "Military, war and the consequences of war" (see chapter 2.5), "The crisis society" (see chapter 2.6), "Transformation in economically uncertain times" (see chapter 2.7) and "Cybersecurity and environmental protection" (see chapter 2.9). Nonetheless, these topics play a role in anticipatory environmental policy, as it is not only important to consider direct environmental impacts when formulating environmental policy measures, but also to keep an eye on the entire environment and be prepared for developments whose impact on environmental and sustainability policy appears uncertain at present.

1.2 Identification and genesis of future topics

The Federal Environment Agency (UBA) has been working on the topic of horizon scanning since 2012. Initially, various international and national horizon scanning activities were evaluated in a concept study (Behrendt et al. 2015). Building on this, a horizon scanning process was designed as part of the Ufoplan project "Horizon Scanning 2.0 - Establishment of a Horizon Scanning System", which is specifically geared towards the needs and requirements of the Environment Department (Federal Environment Agency (UBA) 2016).

Since the concept study was completed, the UBA, together with the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV), has regularly carried out its own horizon scanning:

The **first horizon scanning cycle took place** from 2016 to 2019. The corresponding report[1] covers ten topics, including distributed ledger technologies, virtual and augmented reality, public and private space travel, bio-inspired architecture and settlement development, alternative living concepts and social division (Jetzke et al. 2021). As part of horizon scanning, the topic of artificial intelligence (AI) in the environmental sector was identified as particularly important for the Environment Department and analysed in detail in a separate study (Jetzke et al. 2019a).

The **second horizon scanning cycle** ran from 2020 to 2021. The report[2], which again covers ten future topics, was created primarily under the impact of the Covid-19 pandemic (Jetzke et al. 2023). This context has a strong influence on the report, which is reflected in the broad spectrum of topics. These range from topics that have taken on a new quality in the wake of the Covid-19 pandemic, such as the new regionality and the future of inner cities, to opinion formation in the digital age and resilience as the basis of sustainable societies, as well as technical innovations such as quantum computing and cryptocurrency and the spread of political turbulence, with the threat of a new world (dis)order.

This report presents the results of the **third horizon scanning cycle,** which was implemented from 2022 to 2023. The report covers nine future topics. Once again, the aim was to systematically scan the entire "horizon" and identify emerging topics of key interest for the Environment Department. Topics were also identified that were already known or environmentally relevant, but which have experienced a new dimension of development in the aftermath of the Covid-19 pandemic and/or due to Russia's war of aggression in Ukraine.

From signal to future topic

A horizon scanning process specifically designed for the Environment Department and further developed over the past two cycles was used to identify environmentally relevant future topics (Jetzke et al. 2021; p. 9ff.; Jetzke et al. 2023; p. 9ff.). This is an open-topic

1 Results of the first cycle available at: https://www.umweltbundesamt.de/publikationen/von-blockchain-ueber-raumfahrt-bis-virtuellen

2 Results of the second cycle available at: https://www.umweltbundesamt.de/publikationen/von-quantencomputing-ueber-die-zukunft-der

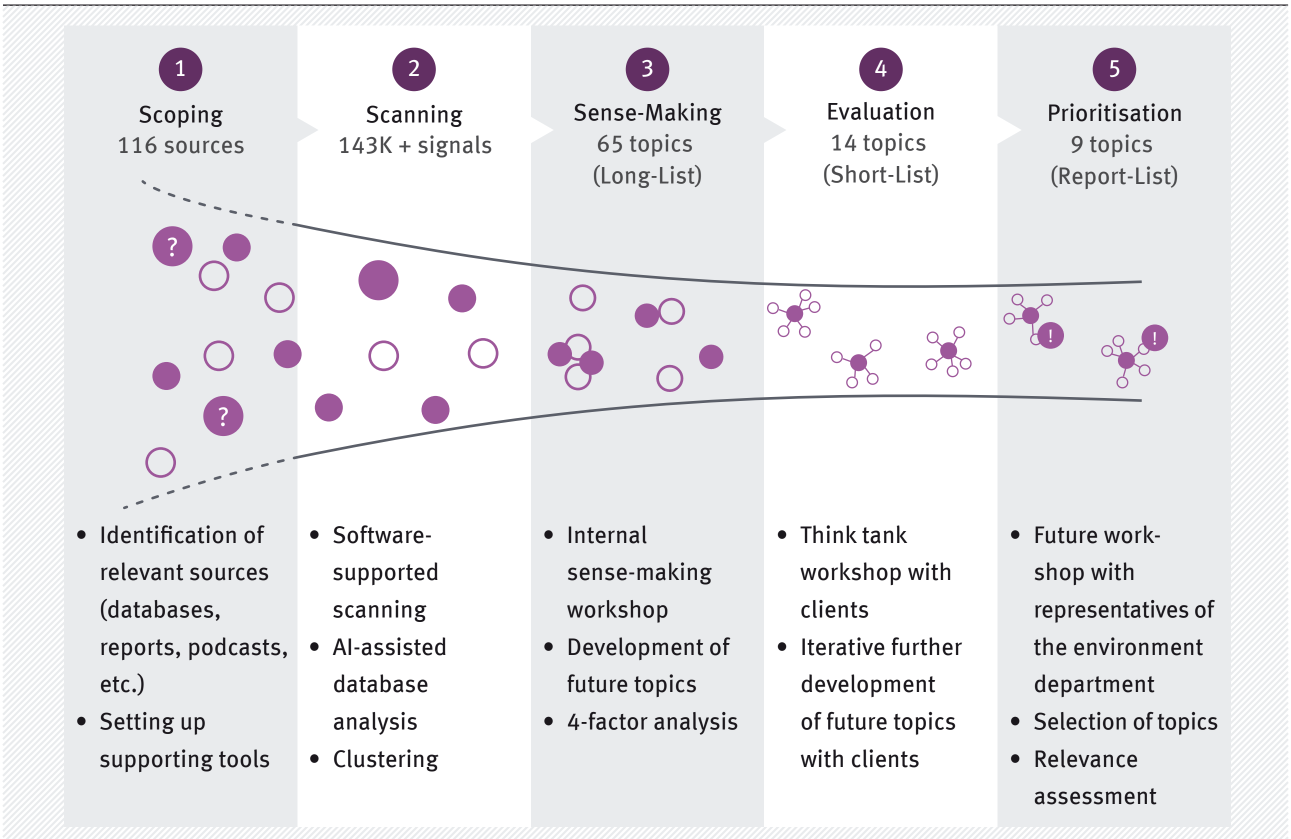
horizon scanning process. The methodical approach ensures the early detection of new, environmentally relevant developments on the basis of so-called weak signals[3], i.e. phenomena that emerge in the observation area of the Environmental Department, but only gain strategic relevance through their consolidation as emerging issues. Emerging issues can be further specified and enriched with additional information so that future issues can be described effectively. An emerging issue is a "situation that has existed for some time, is developing, is not cyclical and can be described (empirically and statistically)" (Behrendt et al. 2015; p. 30).

To identify the future topics at hand, three phases were executed as part of the horizon scanning process: (i) scoping, (ii) scanning and (iii) assessment. The assessment comprises the steps of sense-making, evaluation and prioritisation (see Figure 1).

As part of the **scanning process**, the search areas or scan fields – thematic focal points for structuring the scan – were defined, suitable sources to be analysed were selected for each search area or scan field and supporting software tools for the subsequent scanning were stored. When defining the search areas (see Figure 2), particular care was taken to ensure that not only core environmental topics such as water, soil, air or biodiversity were taken into account in the scanning, but also that developments in all those subject areas that could have an impact on the environment from outside were recorded. A total of 116 sources were used for the scanning: 73 RSS feeds (blogs, leading media, social media and statistical surveys), 20 technology assessment (TA) and foresight platforms, 14 podcasts, six conferences and three (scientific) databases. The breadth of sources made it possible to detect new (environmental) political, social and economic developments and also included social and technical innovations.

Figure 01

Current horizon scanning process



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3 For an empirical discussion of the concept of weak signals, see for example van Veen and Ortt (2021).

As part of the **scanning** process, the sources were searched for environmentally relevant weak signals, and the information was pre-evaluated and stored in data pools for further analysis. In total, more than 143,000 signals were detected. The search strategy was based on the following focal points:

- The RSS feeds were scanned with software support based on the search strategy established in the second horizon scanning. For this purpose, more than 100,000 articles were assigned to the scan fields using implemented rules for automated categorisation. The RSS feed data stored in the scan fields was then assigned to thematic clusters based on the article content using an AI tool. From the clustered articles, a subset selected by foresight experts was chosen for the qualitative content analysis. The selection was based on a recognisable environmental reference, the novelty of the information and a recognisable accumulation of articles on the information in question.

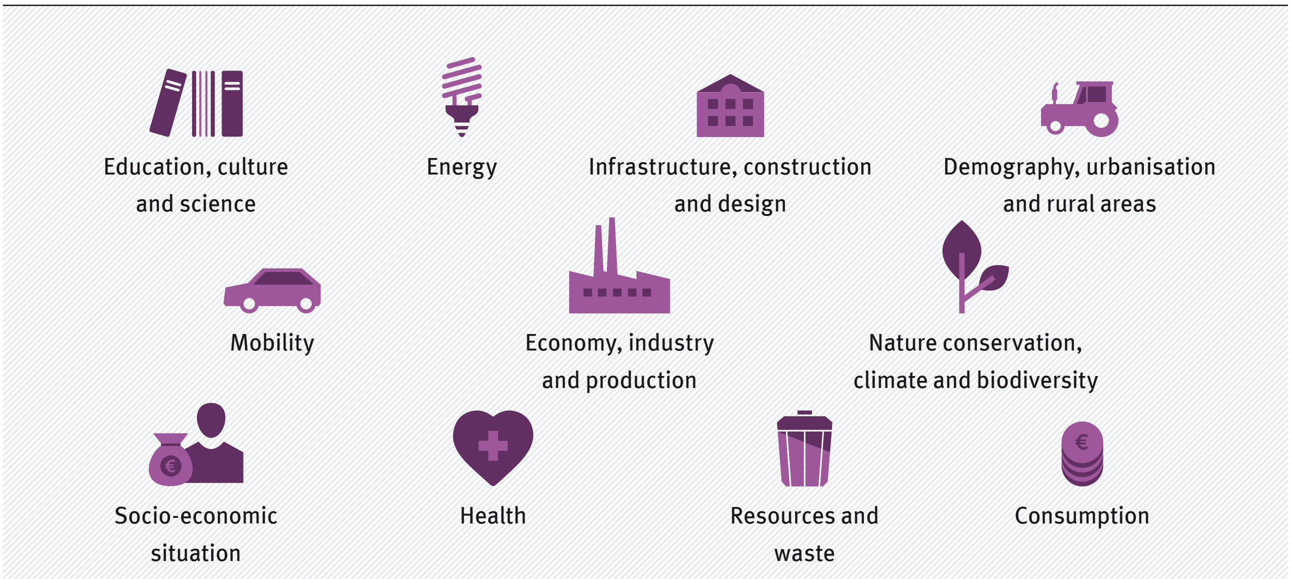
- Sources such as TA and foresight platforms, podcasts, conference websites and reports were reviewed by foresight experts and screened for relevant topics. The same selection criteria were applied as for the analysis of the RSS feeds.

- Databases and foresight journals were searched on the basis of German and English keywords such as trend*, foresight*, innovation*, scenario*, future* etc. and further narrowed down by the search algorithm to the context of sustainability*. The data obtained in this way was collected in a data pool and clustered using AI. The clusters were then searched by foresight experts for environmentally relevant trends and developments using the selection criteria mentioned above.

In the next project step, an **assessment** was carried out in which the relevant information from the scanning was evaluated and clustered. The generation of new topics and trends and their categorisation is essentially an interpretative service that was provided in a sense-making process between the contractors and the Environmental Department as the client. In a first step, qualitative content analysis methods were used to evaluate the information collected, i.e. to condense the weak signals into indications of specific developments or future topics. In addition, co-occurrence analysis was used to identify[4] key topics and thematic cross-references. The results of this analysis step led to an initial selection of 65 future topics (longlist). Once the topics were generated, those on

Figure 02

Scan fields of the horizon scanning process for the Environment Department



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4 Co-occurrence analysis is a method for investigating relationships between terms or concepts in a specific text corpus or data set. A co-occurrence analysis identifies terms that frequently occur together. This makes it possible to recognize patterns and relationships between these terms.

the longlist were evaluated on the basis of signal-specific knowledge with regard to the following factors:

- Topic status: How current is the topic or how dynamically is it developing?
- Topic horizon: In what period of time is the development likely to be established or consolidated?
- Environmental relevance: Does the development have a potentially significant environmental impact?
- Environment Department readiness: Is the topic already on the Environment Department's agenda?

The results served as the basis for a think tank workshop with the UBA and BMUV (evaluation step). During the workshop, the longlist topics were discussed, further developed and supplemented, particularly with regard to their environmental relevance and environmental readiness. As a result, 14 future topics (shortlist) were identified and further developed, which are highly environmentally relevant when compared to the other topics and have a high novelty value for the Environment Department.

The topics on the shortlist were then refined in an iterative process and supplemented with emerging issues. The future topics from the qualified shortlist were then discussed in a future topics workshop with 28 representatives of the Environment Department and further condensed (prioritisation step). The decisive selection criteria were the questions of whether the topics were sufficiently relevant from the perspective of the Environment Department, whether they were already on the environmental policy agenda and whether they were cross-cutting issues that affected several specialist areas of the Environment Department.

The results of the assessment are the nine future topics presented in this report:

1. Lab-grown future
2. The future of seawater desalination
3. Maritime algae farming
4. Democracy in danger
5. Military, war and the consequences of war
6. The crisis society
7. Transformation in economically uncertain times
8. Internet of the future
9. Cybersecurity and environmental protection

Following the horizon scanning process, the selected future topics were developed in greater depth. Literature research and source analyses were carried out for each topic in order to present the topics and their individual environmentally relevant aspects in a well-founded manner. In addition, topic-specific contributions from the speakers and the discussions with the conference participants of the UBA future topics conference "Die Zukunft im Blick. Konferenz für eine vorausschauende Umwelt- und Nachhaltigkeitspolitik"[5] were also incorporated into the development of the future topics.

As a result, the report provides an overview of nine future environmental policy issues, an initial assessment of possible environmental impacts and initial recommendations for further work in the Environment Department. Finally, this report also provides interested members of the public with information and suggestions for further discussion of emerging future environmental issues.

However, the results of the horizon scanning process are only a first step in the direction of forward-looking policy-making to exploit the opportunities that future topics offer for the environment and to address their challenges and risks for the environment as early as possible. The central aim of the process was to identify future issues. Subsequently, the developments presented here can be used as a starting point for further in-depth scientific analyses, for example, to systematically assess direct and indirect environmental impacts and thus prepare the scope for environmental policy and options for action in a holistic manner. This can also be achieved through the use of strategic foresight methods (Keppner et al. 2020). Scenario studies can also help develop alternative development paths into the future or images of the future to support decision-making processes and adapt long-term strategies to different possible futures.

5 https://blick-in-die-zukunft.net/

2

Future topics

2 Future topics of the third horizon scanning cycle

The nine future topics identified are presented in a standardised structure to ensure clear structuring and comparability.

Trend: Each future topic is reduced to its core statements and their possible direction of development. In addition, the emerging issues of the trend are introduced in bullet points.

In a nutshell

- The key findings are summarised here in a concise form and offer a compact overview of the main aspects of the respective future topic and their key environmental impacts. This summary serves as a guide and offers readers an initial impression before they delve into the detailed analysis.

Background

The section is dedicated to the background of the future topic and also contains an outlook on possible future developments. It clearly shows how the topic came about, how it has developed, which factors influence it and what a "look into the future" could look like.

Emerging Issues

The emerging issues represent formative, emerging developments within the respective future topics and focus on emerging challenges and opportunities, particularly with regard to the environment. Environmental impacts are explicitly presented here in order to highlight the relevance of the topic. The aim is to identify the potential risks and opportunities associated with the emerging issues and to highlight new developments that can be expected in the coming years.

Conclusion

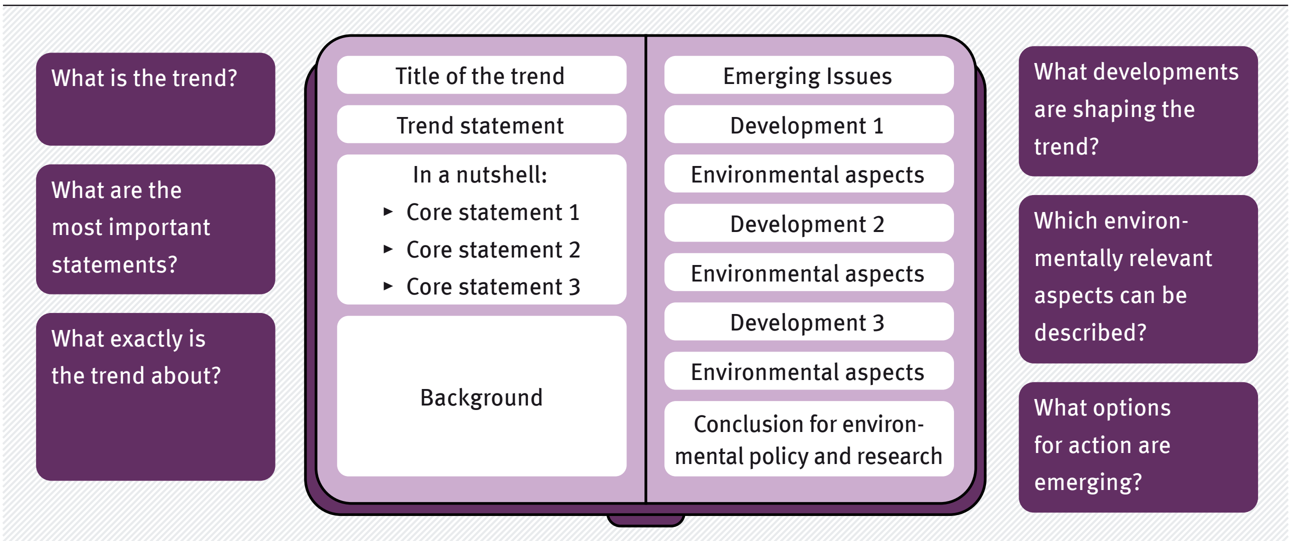
The presentation of each future topic is rounded off with a conclusion that summarizes the findings and establishes a link to the environmental policy framework. This section focuses on the political measures and options for action which may be necessary in the coming years to meet the challenges and opportunities posed by the respective topic.

Literature

The sources used in the respective chapters are listed at the end of the report. They substantiate the statements made and contain further information.

Figure 03

Structure of the description of future topics



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2.1 Lab-grown future

Trend: In vitro meat is just the beginning: more and more foods such as fish, eggs, milk, cheese, ice cream and chocolate, as well as materials such as leather, wood and cotton, can be produced in the laboratory in cell factories. In the future, cell factories will also be used to produce energy and fuels. What might a future look like in which resources are obtained in bioreactors? What are the risks and potentials of the new production processes? And what role can laboratory-produced materials, food and other products play in the transformation to a sustainable society?

Emerging Issues

- Food from the cell factory
- Materials from the cell factory
- (Cell) factories for the lab-grown future

In a nutshell

- Microorganisms have been used by humans for thousands of years. For example, the production of bread, cheese, dairy products, wine, vinegar and beer is only possible through the use of bacteria, yeasts and moulds. The microorganisms act as small factories that produce a variety of substances when fed with the right substrates (equivalent to raw materials) in a suitable environment (usually a container or bioreactor).

- The commercial use of such cell factories for the industrial production of biomolecules is known as biomanufacturing. This is where the Lab-grown Future comes in, integrating the manufacturing processes of precision fermentation and tissue engineering to produce complex tissues, foods and materials. In the future, customisable cell factories could be used to produce a wide variety of tailor-made products for the agricultural, food, materials, energy and pharmaceutical industries.

- Biomanufacturing offers the potential to avoid the negative environmental impact of conventional production processes, for example by reducing interference in existing ecosystems and avoiding animal suffering. At the same time, the mechanised laboratory processes create other problems for the environment, particularly with regard to energy and resource consumption. However, a complete substitution of conventional production is not to be expected in the lab-grown future in view of the energy-intensive, costly production processes.

Background

While the early beginnings of the use of microorganisms for the production of food can still be described as “field experiments” – including, for example, the production of wine from a mixture of rice, honey and fruit in China 9,000 years ago – the development and implementation of biotechnological innovations in recent decades has become common practice in the production of customised industrial products, such as amino acids, insulin, enzymes or citric acid (Graf and Lohmann 2021). Production has increasingly shifted to the laboratory or takes place under strictly controlled laboratory conditions. This industrial application of biological systems, e.g. microorganisms, cells, or enzymes, for the commercial production of biomolecules for the agricultural, food, materials, energy and pharmaceutical industries is known as biomanufacturing. Biomanufacturing is classified as industrial or white biotechnology.

Historically, there have been four innovation cycles in biomanufacturing, which differ in terms of product types, production platforms and processes (Zhang et al. 2017):

- Biomanufacturing 1.0 – At the beginning of the 20th century, primary metabolites such as butanol, acetone, ethanol and citric acid are produced industrially for the first time by monoculture fermentation.
- Biomanufacturing 2.0 – From the 1940s, more complex secondary metabolites such as the antibiotics penicillin, tetracycline and streptomycin can also be produced and purified using mutated fungi and bacteria.
- Biomanufacturing 3.0 – Larger biomolecules, proteins and enzymes such as insulin, growth hormones and DNA polymerase can be produced in genetically modified cell cultures and microorganisms from the 1980s onwards.
- Biomanufacturing 4.0 – Since the 2000s, precision fermentation and tissue engineering have been used to produce increasingly complex organic tissues, food (components) and materials, e.g. vitamins, haemo- and milk proteins and in-vitro meat.[6]

This is where Lab-grown Future comes in and picks up on the current developments of the fourth biomanufacturing innovation cycle. To date, one of the main drivers of this development has been the start-up-dominated innovation activity surrounding in-vitro meat and other foods produced in organic factories, such as fish and milk and dairy products. The biotechnology sector has also benefited indirectly from the Covid-19 pandemic: findings and innovations from the field of vaccine development could also play an important role in the context of a lab-grown future in the medium term.

Production process of the lab-grown future

More and more researchers and start-ups are exploring new ways of producing industrial organic products via biomanufacturing. They are using two different manufacturing processes, precision fermentation and tissue engineering, and are constantly developing them further.

In **precision fermentation**, microorganisms can be genetically "programmed" in the laboratory to produce complex organic molecules (Tubb and Seba 2019). In this way, food components such as proteins, lipids and carbohydrates can be produced, as well as biobased basic chemicals (Ewing et al. 2022; Augustin et al. 2023). Genetic modification of microorganisms is an elementary component of precision fermentation. In the first step of precision fermentation, genetic information on the desired proteins is extracted from a database. In simplified terms, this can be understood as building instructions to enable microorganisms or other cells to produce the corresponding proteins. The information is introduced into the microorganisms or cells using genetic engineering. Under the right conditions – including temperature, oxygen content and pH value – the microorganisms or cells are cultivated in fermenters (bioreactors) and supplied with nutrients. With an optimal supply, these then act as microfactories and synthesise the desired biomolecules.

In addition to the resources required for the construction of the fermentation plants, the environmental impact of precision fermentation is primarily caused by the operation of the bioreactors. The energy required to maintain an optimum process temperature is particularly important here (Reketat 2022). Another hypothetical risk is the possibility of the unintentional release of genetically modified microorganisms into the environment. This is a hypothetical case, as the systems (bioreactors) are normally closed and the

6 For in-vitro meat, see "The future at a glance: Meat of the future. Trend report on the assessment of the environmental impact of plant-based meat substitutes, edible insects and in vitro meat", https://www.umweltbundesamt.de/publikationen/die-zukunft-im-blick-fleisch-der-zukunft

organisms used have no contact with the environment per se. In addition, the microorganisms normally die quickly without the bioreactor environment. However, little is known about possible environmental effects to date (Federal Association of the German Food Industry (BVE) 2023).

The products of precision fermentation are generally intermediate products that are further processed industrially. Collagen proteins are used for the production of leather and milk proteins are used for the production of cheese. The end products, in this example leather or cheese, normally no longer contain viable organisms, but may contain genetically modified DNA. Particularly in the context of food, this can lead to potential consumers rejecting the products. However, it is assumed that the consumption of products produced using white genetic engineering – including precision fermentation – does not pose health risks per se (Hüsing et al. 2017).

Tissue engineering allows a wide variety of complex tissues to be grown "in vitro" on a cell culture basis outside the biological organism. These include in vitro meat and fish (Jetzke et al. 2019b; p. 47ff.; Jetzke and Dassel 2023) but also leather products (Jakab et al. 2019) and wood (Beckwith et al. 2022). In contrast to fermentation, in which microorganisms or cells are used as chemical factories to produce proteins and other substances, tissue engineering involves growing the desired biological tissue directly in a petri dish. This requires stem cells from the target organism, for example a cow, to produce in vitro meat or leather. The cells are typically applied to a carrier scaffold, supplied with a nutrient medium in a bioreactor and, if necessary, stimulated so that they multiply (proliferation) and form the desired tissue (differentiation) - e.g. meat from muscle fibres or leather from collagen.

Tissue engineering generates various environmental impacts that are largely attributable to the operation and, in particular, the energy requirements of the bioreactors. The majority of the energy required is needed in the context of process control; this includes temperature control and the mixing and aeration of cell cultures (Treich 2021). While significant energy savings were assumed in the early phase of research into in vitro meat, current studies paint a different picture and predict that, depending on the type of meat produced, the energy requirement in production is around 35-400% higher than in conventional production (Jetzke et al. 2019b). Other products that could be produced using tissue engineering can also be expected to require a relatively high amount of energy. In terms of animal welfare and acceptance, but also in the context of environmental impact, the type of culture medium also plays a key role. Currently, the most efficient culture medium for the propagation of cells in the laboratory is fetal bovine serum, which is obtained from the blood of calf fetuses (Jetzke et al. 2019b; Menhart 2023). The collection process involves considerable animal suffering for both the dam and the calf foetus. This can lead to some consumers rejecting tissue engineering products (such as vegetarians and vegans) (Whiley 2023).

The lab-grown future is picking up speed

Although fermentation has been used for a long time in cultural history, the further development of this process and the use of **precision fermentation** to mimic or create new biomolecules is relatively new. However, developments in this area are more dynamic and more advanced than in the field of tissue engineering.

In the field of precision fermentation, the first "animal-free"[7] dairy products, which have recently become available in some regions, including the USA and Israel, have been the focus of media attention (Smith et al. 2024). In 2020, milk proteins from precision fermentation were approved by the Food and Drug Administration (FDA) in the USA (German Bundestag 2020). Other proteins from precision fermentation, which could be used for the production of egg, meat or fish products, for example, are not yet on the market. However, it is assumed that the technology for this has already been validated and is being used in pilot projects (Smith et al. 2024).

The start-up scene also reflects the dynamic situation: in 2022, 62 companies focusing on precision fermentation were already active worldwide (Carter et al. 2022; p. 22f.). More than half of the companies involved in the precision fermentation of alternative proteins were founded between 2020 and 2022 (Car-

7 The extent to which the declaration "animal-free" is possible for (food) products from precision fermentation has not been conclusively clarified.

ter et al. 2022; p. 21). In addition, established large companies in the meat, food and biotechnology industries are also becoming increasingly involved in the development and marketing of foods from precision fermentation, e.g. Nestlé (Hiessl and Rübberdt 2023; p. 12). This can lead to a faster development of new international markets outside the USA and a faster introduction of food innovations.

Even though many of the newly founded companies and start-ups do not yet have products on the market, the conditions for the further spread of fermentation products in food and other industrial products are considered to be good (Tubb and Seba 2019). The cost of producing a specific protein using precision fermentation has fallen from USD 1 million/kg of protein in 2000 to around USD 100/kg in 2018. Costs are expected to fall further, to less than USD 10/kg protein by 2025 (Tubb and Seba 2019). Investment in precision fermentation companies and technologies is growing strongly: over the past four years, between USD 222 and 938 million has been invested in the sector annually (Hiessl and Rübberdt 2023). However, most of these investments were made in North America, with Europe lagging far behind in second place. In total, USD 2.9 billion was invested in North America between 2013 and 2022, compared to USD 0.4 billion in Europe over the same period (Smith et al. 2024). In contrast, Europe is the leader in public funding for research and commercialisation of innovations in the field of precision fermentation (Smith et al. 2024). In addition, the European Parliament's Committee on Agriculture and Rural Development (AGRI) explicitly included precision fermentation products in a briefing on the EU protein strategy, which should encourage research and innovation in this area and reduce the regulatory burden on the industry (European Parliamentary Research Service (EPRS) 2023).

The global market for precision fermentation is currently estimated to be worth a low single-digit billion amount, with significant growth forecast for the coming years. By 2030, the market could reach a volume of USD 36 billion (Markets and Markets 2022). Considering these developments, it is not unlikely that more precision fermentation products will make it onto the shelves in the EU and Germany in the near future.

Cell culture-based foods such as meat or fish and materials such as wood or leather, which are produced using **tissue engineering**, are not yet commercially available or produced on an industrial scale. Development is still in its infancy and is mainly concentrated in start-ups, research institutes and universities. The positive premarket consultation by the Food and Drug

Administration (FDA) in the USA for in vitro chicken meat from the company UPSIDE Foods[8] in 2022 (FDA 2022) was an important step towards the market maturity of a cell culture-based product. On this basis, further cell-based products can be evaluated with regard to their safety in the future. However, investigative research continues to question whether the company will be able to produce whole pieces of meat in the near future (Reynolds and Fassler 2023).

The first entrepreneurial impetus for cellular production was provided by the founding of the first start-up for in-vitro meat in 2011, just over ten years ago (Stephens et al. 2019). In 2013, the first cell-culture-based burger patty was produced by the start-up Mosa Meats at a cost of around USD 300,000. Since then, the cost has fallen significantly. However, for future industrial production of in vitro meat, the estimated cost of a burger patty is still around USD 18 (USD 63/kg of meat) (Garrison et al. 2022). This means that in-vitro meat is not competitive in direct comparison with conventionally produced meat, but could become established in niches. Prices for other cell culture-based products, e.g. wood or leather, are not known.

A look into the future

In recent years, various **materials** have been successfully produced using precision fermentation (PF) and tissue engineering (TE), although most of them are still experimental. These include plant tissues such as wood (TE) (Beckwith et al. 2022) and cotton fibres (TE) (Varanasi 2023) animal fibres for "animal-free" skins or wool (PF) (Mundell 2022) and cell-based (TE)[9] and collagen-based (PF)[10] leather. These products are often still (very) far from market launch, as they are at an early stage of development; this applies in particular to materials that are to be produced using TE. However, experimental collaborations are increasingly producing concept studies that explore future potential uses and show where the journey can take us. This includes Korvaa, a transdisciplinary collaboration between science, industrial design and art, which has developed headphones made exclusively from microbially produced materials, including protein-based spider silk (PF) (MaterialDistrict 2019).

In the area of **precision food fermentation**, the focus is currently on the development of proteins. In the USA, more than 30 "animal-free" dairy products are already available in retail stores, e.g. ice cream, milk and cheese (Hiessl and Rübberdt 2023; p. 19). In addition to dairy products, egg and heme proteins (PF) will also gain in importance in the coming years. Lipids (oils and fats) and carbohydrates (PF), on the other hand, are still at an early stage of development and it is likely to be some time before such products come onto the market. The market launch of cell culture-based products (TE), in particular in-vitro meat, is likely to be in the distant future.

The dynamic developments and innovations in the field of biotechnology and biomanufacturing could lead our society and economy into a lab-grown future in the medium to long term, in which almost any product can be made to measure with the help of customisable cell factories or cell lines. Precision fermentation in particular is a promising candidate for competitive product innovations. Research is already being conducted into "**new cell factories**" that could expand the possibilities of a lab-grown future and enable an even broader product range in the future (Graf and Lohmann 2021). From food to platform chemicals and new materials to energy sources, everything seems possible.

With a view to the impact of these developments on environmental policy, the following Emerging Issues section addresses the following questions:

1. What food will we be getting from the lab in the future?
2. Which materials can be produced in the laboratory?
3. What will future biomanufacturing processes make possible?
4. What consequences could these developments have for the environment?

Emerging Issues

The journey towards a lab-grown future can bring significant changes, whether in the replication of natural materials and foods in the laboratory or in the availability of various other chemicals and substanc-

8 https://www.upsidefoods.com
9 https://www.vitrolabsinc.com
10 https://www.modernmeadow.com

es through cell processes. While shifting production from natural environments to the lab could avoid some of the negative environmental impacts of existing technologies and processes, lab-based innovations also come with their own risks and disadvantages for the environment.

1. Food from the cell factory

As the world's population continues to grow (UN News 2024), so too does the demand for food. The agricultural production of food, particularly in the context of the livestock and meat industry, has a number of negative environmental impacts. Today, food production already accounts for around one third of global greenhouse gas emissions (Dwyer 2023) and increasing production volumes while production conditions remain the same would further exacerbate the climate crisis. Agriculture is a major reason why six out of nine planetary boundaries have been reached; (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) n.d.) have been exceeded (Campbell et al. 2017). At the same time, climate change is threatening the food security of the world's population, whether through crop failures due to droughts or the increased occurrence of parasites and pests in agriculture, as rising temperatures and changing precipitation patterns create ideal conditions for them to multiply and spread (Maggiore et al. 2020).

Against this background, the lab-grown future offers various potentials for producing food in the laboratory and meeting the growing food needs of the world's population. In this chapter, fish and milk proteins from the laboratory are used as examples to illustrate developments beyond in-vitro meat, which was already the subject of a UBA trend report[11] (see Background).

Hamburg-based start-up BLUU plans to use tissue engineering to produce fish species such as salmon, rainbow trout and carp in the laboratory (BLUU GmbH 2023). The Californian start-up Finless produces bluefin tuna in the laboratory, the natural form of which is particularly popular for use in sushi (Canon 2023). Both products are in the development stage and are not currently commercially available. According to the manufacturer, BLUU fish products

are expected to receive approval for market launch in Singapore in 2024 and in the USA in 2025 (BLUU GmbH 2023).

Lab-produced fish offers a number of advantages over both conventional fishing and fish from aquacultures. The overfishing of wild stocks, which poses a potential threat to some fish species, is avoided. In 2010, for example, the population of bluefin tuna had fallen to 1.5% of the original unfished population due to overfishing; stocks are already recovering thanks to several protective measures and fishing regulations (Trinh 2023). Laboratory production could take further pressure off wild stocks and contribute to recovery. Laboratory production also reduces animal suffering by avoiding bycatch in fisheries, in addition to the unnecessary killing of the desired fish (World Wide Fund for Nature (WWF) 2022) and could make a significant contribution to the preservation of marine ecosystems.

11 For in-vitro meat, see "The future at a glance: Meat of the future. Trend report on the assessment of the environmental impact of plant-based meat substitutes, edible insects and in vitro meat", https://www.umweltbundesamt.de/publikationen/die-zukunft-im-blick-fleisch-der-zukunft

In 2011, fishing was responsible for around 4% of all global greenhouse gas emissions in food production, particularly through the use of fossil fuels on boats and ships (Parker et al. 2018) – the 179 t CO_2 equivalents emitted correspond to the total emissions of Argentina in the same year (173 t; International Energy Agency (IEA) 2024). This aspect of logistics, including its environmental impact, does not apply to laboratory products. Fish from natural habitats are also often contaminated with pollutants and heavy metals (Lobitz and Rösch 2023). Under laboratory conditions, such contamination could be avoided and would therefore provide consumers with a less contaminated end product.

Although fish farming in aquacultures produces considerably fewer emissions than conventional fishing (MacLeod et al. 2020) and does not harm biodiversity, it is associated with other risks; for example, some natural parasites multiply particularly strongly in aquacultures, which poses risks for fish stocks inside and outside aquacultures and for consumers. Further contamination is caused by the antibiotics used to treat the fish (Buchmann 2022). Outbreaks of farmed animals from aquacultures also pose a threat to surrounding marine ecosystems (Atalah and Sanchez-Jerez 2020). In comparison, production under laboratory conditions ensures that the fish produced cannot be contaminated with parasites and harmful substances, and interaction with natural fish stocks is prevented.

In contrast to in-vitro meat, no life cycle analyses of the environmental impacts of lab-grown fish are yet available; however, in view of the almost identical production method, similarities can be assumed, which means that here too, energy consumption and associated emissions are the main factors to be mentioned. Advantages of the lab-grown product can also be assumed in other environmental impact areas such as land use (Sinke et al. 2023).

While fish from the laboratory, like in vitro meat, is still in the research and testing phase and is not yet available to end customers, some applications of precision fermentation are already much closer to market launch. In cooperation with Perfect Day, Nestlé tested milk produced from “animal-free” whey using precision fermentation in individual locations in the USA in 2022 (Hiessl and Rübberdt 2023).

The global market for dairy products is growing continuously. By 2028, the gross production value of the dairy sector is expected to grow by more than 30% compared to 2023, to USD 111.4 billion (Statista GmbH 2024a). The increasing demand for dairy products has a negative impact on the environment. Cattle emit methane and contribute to climate change, while keeping and feeding cattle requires lots of land and water, with fertiliser and pesticide inputs polluting soil and water (Eberle and Mumm 2021). In an average European diet, dairy products account for around a quarter to a third of the total ecological footprint (Sandström et al. 2018).

Producing the relevant milk components in laboratories could, like in the field of in-vitro meat and lab-produced leather (see Emerging Issue 3), eliminate or at least reduce many of the negative environmental impacts associated with cattle breeding, as farm animals would no longer be required, provided that fetal bovine serum is not used as a nutrient solution. The use of sustainable, laboratory-produced proteins can play an important role in tackling the global problem of malnutrition and undernourishment (Food and Agriculture Organization of the United Nations (FAO) et al.). Compared to plant- or animal-derived proteins, microbial proteins from precision fermentation are less susceptible to external influences such as droughts or pandemics and are not dependent on the presence of fertile soil or healthy livestock (Banks et al. 2022).

The addition of microbially produced milk components also ensures that “animal-free” dairy products taste exactly like their animal counterparts, which would significantly increase acceptance among consumers. At present, many plant-based dairy products (such as those made from soya or oats) do not meet the requirements of milk: for example, they are not equally soluble, taste bitter or lack important amino acids and are less easily digestible (Boukid et al. 2023). Enzymes from precision fermentation can also make plant-based dairy products more viscous and nutritious and can be used to produce vegan cheese, as done by the Berlin start-up Formo[12] (Boukid et al. 2023).

These opportunities for the environment are also offset by various disadvantages. Laboratory-based food production is a highly technical process that requires considerable amounts of energy, causes emissions and has a negative impact on the environment. Shifting agricultural production to the laboratory creates dependencies on highly specialised technologies with high energy requirements, which could lead to a supply crisis in the event of an energy crisis, for example. Social consequences may also arise, for example through a prospective reduction in demand for conventional agricultural products, which could place an economic burden on regions with a strong agricultural character and fundamentally change the cultural landscape. The indirect effects of such a development, for example on biodiversity and nature conservation, must also be considered, as existing monocultures for the cultivation of animal feed, for example, are ecologically detrimental (Haller et al. 2020). There is also a risk that the further mechanisation of food production will further increase consumers' alienation from nature and the origin of their food (Alvaro 2019).

Precision fermentation has a fundamental advantage over tissue engineering, both in terms of the potential marketability of products and with regard to the ecological footprint: while tissue engineering requires the entire useful mass of the target product to be produced in the laboratory, precision fermentation produces individual food components or chemicals, some of which only need to be added to the end product in small doses, such as milk proteins for artificial milk. For one kilogram of end product, the required proportion of precision fermented cell product is between 10 and 70 grams (Good Food Institute (GFI) 2023). This makes it possible to bring end products with precision-fermented ingredients to the market at competitive prices (Albert Schweitzer Foundation 2019). The "dilution" of precision fermentation products in end products also ensures that the ecological footprint of the end product is relatively smaller than that of the material produced. However, before precision fermentation can establish itself on a large scale and herald the lab-grown future, bottlenecks in production capacity in particular must be overcome. This is currently far too small to meet the potential demand for the products produced.

In the case of precision fermentation, it must also be clarified whether the food produced is to be considered genetically modified. This question is decisive for the approval procedure for new foods from precision fermentation in the EU: foods are either approved as are "novel foods"[13] or "genetically modified foods" (European Commission (EC) 2003). The key factor is the degree of separation of the produced raw materials from the producing microorganisms and what limit value is set for DNA residues. This question is currently still unresolved and is one reason why start-ups in the field of precision fermentation often first consider entering the market in other regions with presumably more innovation-friendly guidelines, such as Singapore or the United States (Ronchetti et al. 2024).

Apart from regulatory aspects, many people consider the use of genetic engineering to be fundamentally problematic. The reasons for rejection range from a perceived "unnaturalness" to general technological scepticism to possible, unforeseeable long-term consequences for health and nature (Renn n.d.). What is relevant here, however, is that the assessment of genetic engineering differs greatly depending on the area of application: While so-called "green" genetic engineering covers its use in food production and is viewed with disapproval by the majority of people, "white" genetic engineering refers to its use in special production processes, such as the production of enzymes for detergents; this area of application receives considerably less criticism from the public (Renn n.d.). Thus, the question of the end product produced plays a crucial role in the social acceptance of genetic engineering – and therefore also of precision fermentation.

2. Materials from the cell factory

In the lab-grown future, the production of various materials in the laboratory is possible and by no means limited to food. Advances in precision fermentation in particular make it possible, at least in theo-

12 https://formo.bio/
13 According to EU Regulation 2015/2283, these are foods that were "not used for human consumption to any significant degree in the Union before 15/05/1997" (paragraph 5) (European Commission (EC) 2015).

ry, to produce an almost unlimited variety of materials (see background). Here, the laboratory materials wood and leather, which are already under development, will be considered as examples to provide an overview of the environmental impact of different processes and when replacing a plant-based and an animal-based material.

In 2022, a research team at the Massachusetts Institute of Technology (MIT) succeeded in creating cells of the zinnia, a type of flower (*Zinnia elegans*), in the laboratory and 3D printing them into different shapes to achieve different material properties (Beckwith et al. 2022). The process used is essentially the same as tissue engineering. The declared aim is to use the successfully tested process for the laboratory production of wood in the future (Berry n.d.). The human need for and use of wood as a resource has had and continues to have a significant impact on the environment: since the beginning of human civilisation, the earth has lost around half of its forested area (Crowther et al. 2015) and the vast majority of the remaining semi-natural forests are degraded (Watson et al. 2018). Forests are an indispensable part of the ecosphere and make a significant contribution to regulating the Earth's climate. They also provide habitats for a large number of species and play a central role in the water cycle (Food and Agriculture Organization of the United Nations (FAO) 2020a). Despite their important role, forests worldwide are increasingly threatened by a growing world population, more efficient deforestation methods, the global timber trade and, in particular, the demand for agricultural land (Crowther et al. 2015; López-Carr 2021). Forests are also under considerable threat from man-made climate change (Hartmann et al. 2022). Without changes in human usage behaviour, all of the world's forests could disappear in 100 to 200 years (Bologna and Aquino 2020). Given the importance of forests for the environment, ways must therefore be found to reduce deforestation and degradation globally.

Wood has so far been very attractive as an energy source and building material, not least because of its widespread availability and low cost (Beckwith et al. 2022). Value creation in the global wood market is estimated at EUR 147.6 billion in 2023, and an average annual growth rate of 3.69% is forecast up to 2028, resulting in value creation of EUR 176.9 billion (Statista GmbH 2023a).

In view of increasing demand and simultaneously dwindling natural wood resources, shifting the production of wood from the natural environment to the laboratory can thus help to meet the global demand for wood, create an alternative to extracting wood from forests, take land use pressure off endangered ecosystems (e.g. Amazon rainforest) and contribute to the preservation of forest areas. In addition, the laboratory-based production of wood offers opportunities to reduce waste products, as the material can be produced in the required quantity and form and little to no waste is produced during extraction and processing (Beckwith et al. 2022). Organic emissions and pollution such as wood dust would be eliminated, and wood from the laboratory would be usable and available – regardless of the negative effects of climate change on existing forests – while maintaining the same quality (Müller-Degenhardt 2021).

Another material whose laboratory-based production is emerging is leather. In contrast to other application examples of the lab-grown future, there are approaches from both tissue engineering and precision fermentation in this area: the Californian start-up VitroLabs[14] produces leather from bovine stem cells, i.e. engages in tissue engineering. Companies such as Le Quara[15] from Peru or Bucha Bio[16] from New York, on the other hand, use microorganisms to produce biopolymers or nanocellulose, from which synthetic leather is produced in the next step (Waltz and Nature Biotechnology 2022).

Natural leather is made from the skin of farm animals, primarily cows (Lau 2023). The production of leather is usually a by-product of meat production. Both require the slaughter of the farm animal, so unprocessed leather already has environmental impacts that are very similar to those of (beef) meat and dairy products. Leather production involves a high degree of land consumption, uses a lot of water and produces a large amount of greenhouse gases due to methane excretion from cattle (Barrantes 2019). In addition to the environmental impact of animal breeding, the subsequent tanning process is also highly energy-intensive and causes up to 90% of total emissions in leather production (Lau 2023). In addition to high energy consumption, the industrial tanning of leather also has other negative environmental impacts: it consumes abiotic (non-renewable) resources, contributes to the formation of harmful ground-level ozone and is potentially harmful to aquatic ecosystems – wastewater from tanneries contains a mixture of harmful organic and inorganic chemicals such as chromium salt, acids, bases, fatliquors and organic tanning agents (Notarnicola et al. 2011). The environmental footprint of one kilogram of chrome-tanned leather includes 60 to 250 litres of water, 37.2 to 210 megajoules of energy, 2 to 2.5 kg of chemical substances converted into waste, and 4.3 to 6.15 kg of solid waste (Corradini et al. 2016). During the production process, around 30% of hide used for natural leather is lost in the form of so-called offcuts, as scars are removed from the leather and the leather is cut to size for further processing (Barrantes 2019).

Artificial leather from the laboratory could counteract these disadvantages in many ways. By dispensing with animal husbandry, the need for land, water and feed can be reduced considerably, perhaps even to nothing. There is significantly less or no animal suffering when stem cells are extracted. No chemical tanning process is necessary and the associated waste etc. is eliminated. Thanks to the ability to produce the target product in the desired quantity and form, there is no waste of leather remnants. However, the various leather production processes have yet to provide evidence that the leather produced actually comes close to the original, for example in terms of durability and robustness (Lau 2023). However, since it is also possible to genetically optimise materials beyond their natural state, especially with precision fermentation, this goal is at least theoretically achievable.

However, all the possible advantages of biomanufacturing must always be weighed against the environmental impacts described in the background chapter, which inevitably occur in the course of high-tech processes such as those used in biomanufacturing. In order to be able to record these environmental impacts more precisely in the context of individual products, a comprehensive life cycle analysis of the technologies concerned is necessary, which records energy balances, consumption of chemicals and water as well as waste management and compares them with conventional products. This is the only way to weigh up whether the substitution of natural materials with

14 https://www.vitrolabsinc.com/
15 https://leqara.com/
16 https://bucha.bio/

materials from the laboratory is at all desirable from an environmental point of view.

3. (Cell) factories for the lab-grown future

Advances in biomanufacturing will also make it possible to produce a wide variety of other chemicals in the laboratory in the future, in addition to the food and materials already mentioned. Increasing demand for sustainably produced, low-cost chemical raw materials favours various advances in biotechnology (Dudley et al. 2015). Living cells or replicated cell processes form the basis for the production of the aforementioned substances –- in a sense, the cell serves as a factory for the production of specific individual chemicals and products.

Although the processes described above are already highly developed in some areas, there is still considerable untapped potential. Industrial biomanufacturing offers the opportunity to meet the environmental, geopolitical and economic challenges facing the conventional, centralised, industrial production of chemicals. Advances in biomanufacturing allow for cost-effective, decentralised production in smaller facilities (Clomburg et al. 2017) which, among other things, reduces emissions in the transport sector and ensures greater supply security for pharmaceutical raw materials. Decentralisation is important in order to prevent the failure of important supply chains in the context of cyberattacks (see chapter 2.9) or military conflicts (see chapter 2.5). In addition, production in the laboratory offers the possibility of precisely controlling energy and material flows, which enables precise monitoring of production and the recycling of raw materials, for example (Beckwith et al. 2021). At least with regard to the specific production processes of the lab-grown future, environmental impacts could therefore be assessed much more accurately than in conventional production.

Developments in the digital sector are likely to have a significant impact on the lab-grown future. The use of AI, machine learning and digital twins makes it possible to largely automate and machine-optimise testing and manufacturing processes (Rathore et al. 2023) which could have a positive impact on efficiency and resource utilisation (Udugama et al. 2021). However, the high energy consumption of AI technologies must be taken into account here (see chapter 2.8), which must be weighed against the potential savings. There is also a risk that positive environmental impacts resulting from process optimisations etc. will be counteracted by rebound effects if the growth of the sector leads to an increase of the negative environmental impacts of overall production which outweighs the benefits.

In addition to the aforementioned optimisations, research is also focusing on new biomanufacturing processes and new platforms for the production of chemical substances in the laboratory. For example, chemical bases and biofuels can be obtained from methane through “synthetic methanotrophy” (Nguyen and Lee 2021) and thus consume the second most important greenhouse gas after CO_2, making an important contribution to climate protection (Appelhans et al. 2022). Algae (see chapter 2.3) can be used as a platform for the production of enzymes, proteins, hormones, antibodies and other target products (Rasala and Mayfield 2015) and insect cells can also be used as platforms, for example in pesticide production (Drugmand et al. 2012). Egg shells and marine organisms can also be used as scaffolds in tissue engineering – a way to recycle food waste and improve the environmental footprint of the technology (Hembrick-Holloman et al. 2020).

The field of cell-free biomanufacturing promises even more far-reaching innovation potential. The use of living cells in previous manufacturing processes entails limitations, as the cellular survival goals often conflict with the production goals and limit the production potential (Rasor et al. 2021). Not all chemical precursors can be produced in cell-based biomanufacturing in sufficient quantities to meet demand (Dudley et al. 2015). Only a loosening of cell-based production restrictions would make cost-effective laboratory-based mass production of a large number of chemical precursors possible (Rollin et al. 2013; Bowie et al. 2020).

Conclusion for environmental policy and research:

In order to be able to realistically assess the possible consequences of the outlined developments for the environment, continuous, detailed monitoring of the production processes and their environmental impact is necessary to be able to counter problematic developments and exploit potential. In addition to the specific environmental impact of laboratory processes (e.g. through energy consumption), a comprehensive assessment of the energy and raw material requirements of the cell cultures and the nutrients used is also important. Indirect effects, for example on the cultural landscape and society as a whole, must also be considered in order to identify fields of application in which the lab-grown future can make a contribution to a more sustainable society.

From a sustainability perspective, innovations in biomanufacturing are fundamentally faced with the problem that the technologies mentioned primarily serve to substitute raw materials, food and consumer goods that are harmful to the climate and environment as precisely as possible, instead of aiming for a more profound change in consumer behaviour – which would be necessary for a sustainable transformation. Without appropriate control, this makes the lab-grown future susceptible to a variety of rebound effects: the new technologies contribute to an increase in the total amount of raw material available without bringing about savings in conventional production. Although it currently appears that the new products of a lab-grown future could possibly play a role in averting the triple crisis consisting of climate catastrophe, pollution crisis and species extinction, they must be embedded in a larger framework of sufficiency and must not support the continuation of previous consumption patterns as an apparent "green fix".

The opportunities of a lab-grown future for the environment therefore lie less in the complete replacement of products from conventional production, which will hardly be possible across the board in the foreseeable future given the high production costs – complete substitution by 2050 would require 33% of the total renewable energy (RE) available worldwide (El Wali et al. 2024). Instead, the combination of different processes, e.g. biomanufacturing, plant-based alternatives and ecological agriculture, fishing and forestry, offers potential for achieving sustainability and climate targets. The intelligent combination of different measures is particularly relevant here. For example, wood from the laboratory alone cannot guarantee the preservation of endangered forest areas. However, in combination with reduced land use pressure from livestock farming, for example in the form of an overall reduction in meat consumption, partial substitution of leather requirements by means of biomanufacturing, more sustainable agricultural methods, e.g. in the cultivation of soy on uncleared land and environmental protection measures, e.g. for biodiversity, it is quite conceivable that threatened forest areas can be better protected. Environmental policy should therefore focus on the development of cross-sectoral sustainability strategies, taking into account the potential opportunities and risks of the lab-grown future.

2.2 The future of seawater desalination

Trend: Water scarcity is already a problem in many regions around the world and will become even more acute as a result of climate change and our society's increasing demand for fresh water. The desalination of seawater is increasingly becoming a solution for obtaining more fresh water. However, desalination plants produce chemically contaminated waste lyes and are energy-intensive, but are also constantly evolving. Will there be seawater desalination plants in the future that are also environmentally friendly? What opportunities and risks does the use of desalinated seawater pose for the environment and society?

Emerging Issues

- Processes and technologies for seawater desalination on the road to environmental friendliness?
- Brine - problem waste or future raw material?
- Freshwater from seawater desalination: emerging uses

In a nutshell

- Thanks to the virtually inexhaustible resource of seawater, seawater desalination offers enormous potential for counteracting freshwater shortages. There are now around 22,000 plants worldwide that desalinate water for drinking water, industry and agriculture. It is also becoming increasingly important in other sectors, such as the energy sector for hydrogen production.

- However, conventional seawater desalination has a significant environmental impact. Despite increasing efficiency, traditional processes are very energy-intensive and use 99% fossil fuels, which leads to significant CO_2 emissions. Combining desalination technologies with renewable energies and innovative desalination processes, some of which operate on completely different principles, offers promising potential for low-emission seawater desalination.

- Furthermore, seawater desalination produces large quantities of highly concentrated, sometimes toxic brine, which is currently disposed of at sea, often with considerable environmental impact. The latest approaches to using the brine as an energy source, utilising it in fish and algae farming and using the raw materials contained in the brine are very promising.

- However, many innovations for sustainable seawater desalination are often still at the research stage and face economic challenges. Further investment in research, infrastructure development and political support are crucial for more environmentally friendly seawater desalination.

Background

Two developments will pose a challenge to securing freshwater supplies in the future: firstly, a growing global population and increasing prosperity will lead to rising water requirements for energy supply, industry, agriculture and society (Kainrath 2023). It is predicted that this demand is unlikely to be met by freshwater resources and that more than 60% of the world's population will suffer from water shortages by 2030 (Boretti and Rosa 2019).

On the other hand, the natural supply of fresh water is becoming increasingly difficult due to a lack of rainfall and rising temperatures. Water scarcity is already a reality in Europe too: around 30% of Europeans are already affected by water scarcity in an average year. While water scarcity is currently still concentrated in southern Europe and Spain and Portugal will be the hardest hit, it is predicted that by 2050, around 98% of European cities will experience record droughts and regional water scarcity will also increase in Germany (European Environment Agency 2021; Johnson 2021; German Federal Government 2023a).

The desalination of seawater is increasingly being seen as a possible solution to meet the demand for fresh water despite the growing global water crisis. Seawater desalination is a technological process for obtaining drinking water from seawater. This process of removing salts and other impurities from seawater is becoming another option for obtaining drinking water, alongside the extraction of water from rainwater and groundwater, lakes or mountains or the recycling of water. From an environmental perspective, however, desalination technologies generally have a very poor CO_2 footprint, produce chemically contaminated brines and are energy and cost-intensive (Lee and Jepson 2021).

Seawater desalination has been around for a long time. It is said that the history of seawater desalination dates back to the 4th century BC, when the first process for removing salt from water was documented in ancient Greece (Roser 1994). Solar distillation was one of the earliest methods of water desalination. Seawater was evaporated and the condensate was collected as fresh water. Since then, the technology has continued to evolve, with significant advances being made in the 20th century. In addition to a further development of distillation processes, new processes have been developed in which seawater is pressed through a semi-permeable membrane to remove salts. In particular, the introduction of the so-called reverse osmosis method in the 1960s led to the further spread of seawater desalination.

Areas of application and increasing distribution and demand

Seawater desalination is used worldwide for various purposes; large quantities of freshwater are required, for example, for **drinking water supplies** and **industries** such as chemical and food production (International Desalination Association 2011). In **agriculture**, desalinated seawater is used for the irrigation of agricultural land. This enables agricultural activities to be maintained in arid regions. Significant quantities of water are also required for oil and gas extraction. Through desalination, this water can be used in wells for production. *Tourism* is a particularly large consumer of desalinated seawater, especially on islands and coastal areas. It is used to meet the water requirements of hotels and resorts. Desalinated seawater is also used in **emergencies and disaster situations** to provide drinking water when conventional water sources are unavailable or contaminated. The application examples illustrate the versatility and importance of seawater desalination in various areas to meet the water needs of communities, industries and other facilities.

The spread and use of seawater desalination plants has increased worldwide in recent decades. Especially in arid regions and coastal areas affected by water shortages, seawater desalination has played a decisive role in ensuring a reliable supply of drinking water. Today, desalinated seawater is already the only source of water for more than 300 million people worldwide (Macher 2023). The number of operational desalination plants has now risen to almost 22,000 worldwide. The largest are located in Saudi Arabia, Israel, the United Arab Emirates and the USA (Elsner 2023). At 54.1%, the countries of the Middle East and North Africa (MENA) have the largest desalination capacities worldwide. This is followed by America with 19.1%; Europe accounts for 13.4% of global desalination capacity (Statista GmbH 2002; Johnson 2021). While Spain holds 65% of European desalination capacity and is therefore the largest user of desalination, the method has also gained in importance in northern Europe. Germany, for example, accounts for 4% of European desalination capacity (Blue Economy

Observatory 2021). On Heligoland, for example, fresh water and therefore drinking water has been obtained through desalination since 1990 (Blue Economy Observatory 2021; Utilities Helgoland 2023).

The development of the market for seawater desalination shows a rising trend, as the demand for fresh water is growing in many regions worldwide. The global market volume is forecast to increase from USD 19.29 billion in 2021 to USD 32.02 billion in 2027 (Research and Markets 2022). Some important trends and developments in the seawater desalination market are evident, for example, in the steady global growth in the number of seawater desalination plants that are being built to meet the increasing demand for water. The capacity of operational seawater desalination plants has increased exponentially, just a handful in 1980 to around 16,000 in 2019. While less than 5 million m^3 of water was desalinated per day in 1980, the amount rose to around 95.37 million m^3 per day in 2019 (Jones et al. 2019). The increasing desalination capacities are shown in Figure 4. Desalination will continue to gain in importance, particularly in water-scarce areas and coastal regions, not least due to climate change. Large-scale seawater desalination projects are being carried out, particularly in the arid regions of the Middle East, to meet the growing demand for water in order to enable development in the first place (Behrens 2017; Jones et al. 2019). However, there are also smaller projects and decentralised seawater desalination plants to solve local water supply problems. This can also be useful in remote or rural areas.

Use and impact of different desalination technologies
Seawater desalination technologies can be divided into membrane methods and thermal methods (Paál 2020; Glade et al. 2022). The most widely used technology is reverse osmosis (RO), a membrane method in which seawater is forced through a semi-permeable membrane that retains salt and other minerals. The water that flows through the membrane is desalinated and can be used as drinking water. Multi-stage flash distillation (MSF) and multi-effect distillation (MED) are widely used thermal technologies. In these processes, the seawater is evaporated and condensed in several stages to remove the salt. There are also other methods of seawater desalination, such as electrodialysis (a chemical process that separates ions from uncharged solvents and impurities and increases the acid and base concentration while decreasing the salt solution), or freezing processes (where seawater is frozen to produce salt-free ice crystals), but these are less common. An overview of the technologies used is shown in Figure 4 (Jones et al. 2019). It can be seen that reverse osmosis (RO) is used for 69% of the total desalination volume worldwide. Together with the two thermal methods of multi-stage flash evaporation (MSF) (desalinated 18%) and multi-effect distillation (MED) (desalinated 7%), the three methods are used for 94% of the global desalination volume. Other methods, including electrodialysis (ED) and nanofiltration (NF), are rarely used and together account for 6% of desalinated water worldwide.

Figure 4 (Jones et al. 2019) also shows the development of the individual desalination technologies. Since 2000, the number and capacity of plants using reverse osmosis in particular have increased exponentially, while multi-stage flash evaporation has remained at a constant level. In addition to different energy and cost efficiencies, the choice of technology also depends on the salt content of the fresh water types. In addition to seawater, brackish water is also desalinated; this has a lower salt content and plants operate more efficiently if the technology and the fresh water resources are compatible. Large plants using thermal methods are mainly located in the Middle East, as these are best suited to water with a very high salt content, while technologies such as reverse osmosis are good for different types of salinity. The reason for the increased use of the reverse osmosis process is also the better energy and cost efficiency, especially compared to multi-stage evaporation.

Water salination produces around 141.5 million m^3 of brine per day worldwide, which is 50% more brine than desalinated water (Jones et al. 2019). This annual amount is enough to flood Germany to a height of around 30 cm (Mrasek 2019). Most caustic soda (approx. 70.3%) is produced in MENA countries, where desalination plants have the lowest desalination efficiency in comparison, as thermal technologies (MFS; MED) are often used. They are less desalination-efficient than membrane technologies (RO). In addition to the method, the desalination efficiency also depends on the water quality (Jones et al. 2019). The resulting caustic solution is harmful to the environment in that it contains chemicals in addition to salt that are generated during the desalination process (i.e. that have to be used to enable desalination in the first place) and because the caustic solution is often disposed of in the sea, which is the most cost-effective disposal option. There are currently no regulations for the disposal of caustic solutions. The higher salinity and chemicals at the discharge points in question reduce oxygen levels and adversely affect marine organisms.

A look into the future

Seawater desalination allows things to continue as usual. As climate change progresses and freshwater availability becomes more critical, new regions with water supply deficits will also emerge in Europe and Germany. The increasing global water shortage is driving the development of desalination as a resilient alternative to conventional water sources such as lakes and rivers. The CEO of DME, a German think tank on desalination, Claus Mertes, confirms annual growth in the desalination market of around 15% (Goergen 2022). What is already indispensable for 300 million people today (Macher 2023) will be indispensable for water supply in more regions in the future due to climate change and population growth if there are no significant changes in terms of water use and consumption/savings. A 40% discrepancy between drinking water demand and supply is expected worldwide by 2030 (United Nations Environment Program (UNEP) n.d.). This will bring the solution of environmentally relevant problems of seawater desalination even more into focus.

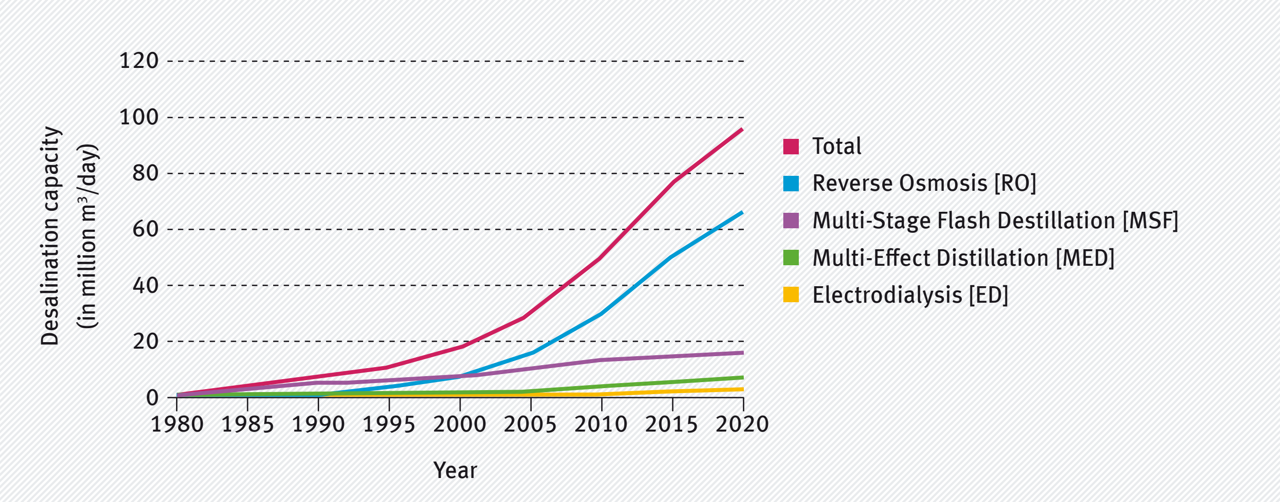
The market is constantly evolving and technologies are becoming more efficient (Jones et al. 2019). In a possible future development corridor, it is conceivable that more renewable energies such as solar will be used for water desalination plants instead of fossil fuels. Advances in research and development could also make it possible to improve the sustainability of processes and make them more cost-effective. Research is also already being carried out into other uses for chemically contaminated waste lye, e.g. for fish farming, or the extraction of minerals such as sodium, magnesium, calcium and potassium from the lye that are important for other areas of production (Jones et al. 2019).

With a view to the impact of these developments on environmental policy, the following Emerging Issues section addresses the following questions:

1. How can new processes and technologies enable seawater desalination in the future that reduces costs, increases energy efficiency and produces environmentally friendly freshwater?
2. What role will brine play in the future development of seawater desalination and could there be other possible uses in the future?
3. What future uses will there be for desalinated water?

Figure 04

Water desalination capacities of the various technologies in operational plants



Source: own presentation according to Jones et al. 2019; p. 1348

Emerging Issues

As discussed above, the importance of seawater desalination to meet the growing demand for fresh water has increased significantly. This also increases the need and demand for environmentally friendly and sustainable desalination. As a by-product of seawater desalination, brine poses a risk to the environment, but also contains valuable resources that have great potential for reuse. In addition, new areas of application are opening up for desalinated water, which can reduce the effects of climate change and other impacts on the environment.

1. Technologies for seawater desalination on the way to environmental friendliness?

Seawater desalination is one of the most energy-intensive methods of water treatment, with annual energy consumption estimated at 75.2 terawatt hours (Nassrullah et al. 2020). This exceeds Berlin's annual electricity consumption in 2022 by a factor of six (dpa 2023). This energy demand is largely covered by fossil fuels (United Nations Educational, Scientific and Cultural Organization (UNESCO) 2014), creating a high CO_2 footprint. In addition to CO_2 emissions, the disposal of brine (see Emerging Issue 2), water extraction and discharge and the construction of conventional desalination methods have negative environmental impacts that need to be taken into account (Jones et al. 2019; Elsaid et al. 2020a; Elsaid et al. 2020b).

A central aspect of the discussion about more environmentally friendly seawater desalination is the use of **renewable energy**. Life cycle assessment studies have shown that switching from fossil to renewable forms of energy in reverse osmosis plants has the potential to reduce negative impacts on indicators such as climate change, ecosystem quality, resources and human health by up to 91% (Nasrollahi et al. 2023). The combination of photovoltaics (PV) and reverse osmosis (RO) is particularly successful. The first large-scale solar desalination plants have already been built, for example in Saudi Arabia. In Western Australia, the use of renewable energies is even mandatory for new desalination plants (Hernandez and West 2022) and coupling is becoming increasingly affordable in general, as the cost of renewable energy will continue to fall in the future and is already generally cheaper than fossil fuels today (Pistocchi et al. 2020). According to a 2015 report by the Global Clean Water Desalination Alliance, the use of renewable energy for seawater desalination could save around 83 t CO_2 per year in 2040 compared to emissions of 218 t CO_2 in 2040 if fossil energy sources are retained (Global Water Desalination Alliance 2015). However, there is still a long way to go before seawater desalination is environmentally friendly, affordable and energy-efficient.

At the same time, a number of more environmentally friendly desalination approaches are emerging from the world of research. These approaches include processes that use the electrical potential of ions in salt water, such as electrodialysis (ED) and capacitive deionisation (CDI). Both techniques are generally more energy efficient as they do not use pressure-based processes such as reverse osmosis. In addition, less chemical pre-treatment is required to remove particles and contaminants, which lowers costs and reduces environmental impact. Other techniques take into account the different solubility of salts and impurities in water depending on the temperature, such as Temperature Swing Solvent Extraction (TSSE), or use the natural osmotic pressure of salt water, such as forward osmosis (FO). In addition to these innovations, existing processes are being optimised: for example, through the use of functional membrane materials, including magnetic and antibacterial membranes, and through the use of biodegradable "green chemicals" (Pervov et al. 2018). The Microbial Desalination Cell (MDC) also offers an interesting alternative to conventional processes. This bioelectrochemical-based desalination system could represent an energy-efficient technology that not only desalinates water with the help of microorganisms (e.g. algae), but also extracts electrical energy and raw materials contained in the water. The by-products hydrogen and biomass are also of interest here (Al-Mamun et al. 2018; Ewusi-Mensah et al. 2021; Imoro et al. 2021; Gujjala et al. 2022; Rossignolo et al. 2022). At the future topics conference organised by the UBA, Claus Mertes from DME, a central contact point for national and international interests regarding seawater desalination, expressed optimism that more environmentally friendly technologies such as microbial desalination could replace established reverse osmosis in the future (Goergen 2022).

Emerging innovations reveal the potential to significantly reduce the environmental impact of seawater desalination. However, these approaches are often still at the research stage and cannot yet be implemented on a large scale. They are also in direct competition with conventional processes, which are often even more economical in the short term, without factoring in external costs (Lee and Jepson 2021). The implementation of these new systems requires intensive research and long-term demonstrations, which should be supported by political measures.

2. Brine – problem waste or future raw material?
For every litre of water obtained from desalination, approximately 1.6 litres of brine are produced. Brine is a heated, highly concentrated salt solution that is often contaminated with heavy metals and a variety of chemicals. The chemicals in the brine usually originate from the water extraction process and are present to a greater or lesser extent depending on the method used. However, this toxic cocktail also contains valuable raw materials, such as lithium, which are of key importance for a sustainable energy future. The extraction of these raw materials from seawater and brine has attracted increased interest in recent years due to the quantity of brine provided by lithium being thousands of times greater quantity compared to land reserves (Morillo et al. 2014; Lim et al. 2023).

At present, brine is generally discharged into the environment, 80% of which is discharged into the sea – with considerable environmental risks. At the discharge points, the higher salinity and increased temperature often lead to oxygen depletion, which endangers marine life (Jones et al. 2019; Hossein Davood Abadi Farahani, Mohammad et al. 2020). Shallow, enclosed and semi-enclosed areas with high biodiversity are particularly vulnerable (Shokri and Sanavi Fard 2023). Another relevant factor is the accumulation of pollutants. Alharbi et al. (2017) were able to detect increased concentrations of heavy metals at a sampling point near the Al-Khafij desalination plant in the Persian Gulf in a sediment study. These environmental risks are increasingly becoming the focus of public debate. In California, for example, seawater desalination projects were halted by protests from social groups (Haddad et al. 2018; Ibrahim et al. 2021; Goergen 2022).

Common methods to reduce the environmental impact include diluting the brine with low-salinity water, including cooling water, wastewater or seawater, and discharging it into regions with strong ocean currents (Panagopoulos et al. 2019; Shokri and Sanavi Fard 2023). However, it is still unclear whether and to what extent these methods can reduce the environmental risks of brine discharge - especially as chemicals are also discharged. In any case, there is a need for regulation here.

More promising are approaches for utilising the brine or the substances it contains. Selected examples of up-and-coming methods from the current research landscape are presented below:

- Agricultural use of brine: the use of (purified) brine that is not contaminated with heavy metals or has already been treated has shown promise in algae and fish farming and in the irrigation of fodder crops and other crops (Shokri and Sanavi Fard 2023). Algae such as spirulina can neutralise minerals and heavy metals contained in the brine (Sánchez et al. 2015).

- Energetic utilisation of brine in salt gradient power plants, also known as “blue energy” plants, whereby electricity is generated along an ion exchange membrane by the salt gradient between seawater and brine, which can be reused for other operational components, for example. Through this use, the plants can not only contribute to better energy efficiency, but also significantly reduce environmental pollution at the same time (Lanjewar et al. 2020).

- Concentrate remediation (“brine mining”): Raw materials such as heavy metals, minerals and rare earths such as uranium and lithium are extracted from the brine using methods such as zero liquid discharge (ZLD) and reused. Thermal evaporation and crystallisation processes are primarily used to concentrate the brine. Temperature Swing Solvent Extraction (TSSE), for example, is a sustainable variant in which the water is extracted using a solvent and then evaporated at low temperatures (Boo et al. 2020). High quality requirements for extracted raw materials and the associated costs mean that brine mining is primarily used in internal company recycling processes, for example in the recovery of sodium and chlorine as sodium hydroxide and hydrochloric acid (Chandler 2019; Pistocchi et al. 2020; Del Villar et al. 2023).

- Minimising the use of harmful chemicals through antibacterial membranes, additional pre-purification stages or the use of environmentally friendly chemicals (“green chemicals”), which reduce the environmental impact of the brine due to their biodegradability (Pervov et al. 2018).

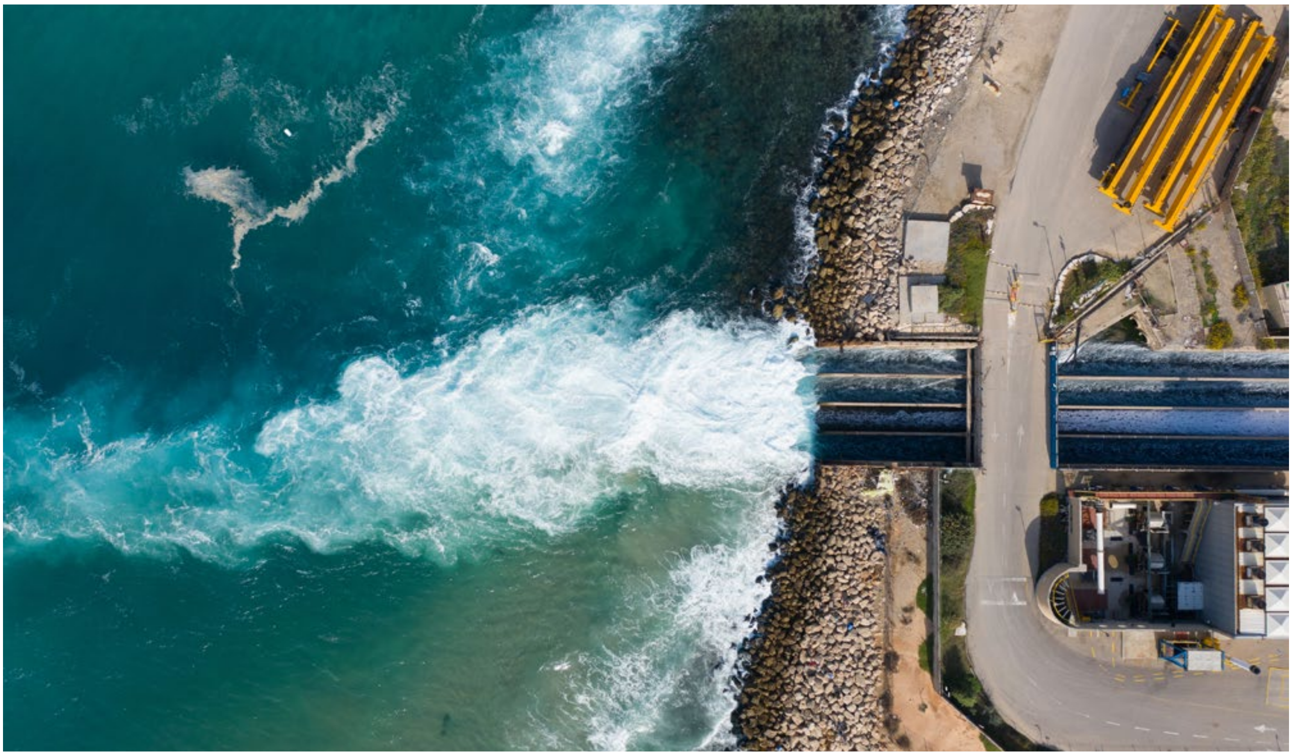
The approaches presented for the more environmentally friendly treatment of brine are promising, but still involve challenges and trade-offs in their current state of development. The use of green chemicals requires compromises in efficiency (Pervov et al. 2018), while the use of brine in fish farming requires stricter monitoring and control to avoid the accumulation of toxic substances in the fish. Current ZLD processes are energy-intensive and therefore pose potential environmental risks (Shokri and Sanavi Fard 2023). The low concentrations of uranium and lithium in the brine make its commercial use difficult. Further research is needed to make these new approaches more competitive with conventional methods of discharging brine into the sea and to find a sustainable solution away from brine “disposal” towards brine “utilisation”. As an intermediate step, the regulation of disposal must be addressed.

3. Freshwater from seawater desalination: emerging uses

In regions with scarce alternative water sources or high demands on water quality, desalinated seawater is becoming increasingly important for drinking water supplies, industry and agricultural irrigation. There is less focus on saving water. New forms of use could further increase the contribution of seawater desalination to overcoming the challenges of climate change, for example in the production of “green hydrogen” using renewable energies or in the area of “desert greening” (the re-greening of desert areas). Both examples of use are examined in more detail below:

- Hydrogen production from seawater: it is non-toxic, storable and contains almost three times as much energy as gasoline (Asendorpf 2023). However, far more importantly, it does not emit CO_2 during its use: hydrogen (H2) is considered a promising renewable energy source and a key element for the implementation of the Paris climate targets and CO_2 neutrality in the EU and Germany (Federal Ministry for Economic Affairs and Energy (BMWi) 2020; European Commission (EC) 2020a; Tak et al. 2022). However, this only applies to the use of “green” hydrogen, the production of which currently requires highly purified water. In the net-zero scenario, this would require around 8 billion m^3 of highly purified water for global hydrogen production by 2050 (International Energy Agency (IEA) 2023; Ramirez et al. n.d.). Although this corresponds to less than half of the current water demand for oil and gas production, the use of existing freshwater resources to meet this demand is considered neither sustainable nor sufficient, especially in light of climate change (Stratmann 2021). For this reason, and particularly in water-scarce regions, the International Energy Agency (IEA) recommends the desalination of seawater in the Global Hydrogen Review 2022 to obtain the required high-purity water (International Energy Agency (IEA) 2023). However, the hydrogen obtained in this way can only be considered “green” if the seawater desalination is also “green” – a relevant aspect that is often overlooked in the debate.
  The majority of seawater desalination plants are powered by fossil fuels (United Nations Educational, Scientific and Cultural Organization (UNESCO) 2014). However, one technical innovation, direct H2 electrolysis, has the potential to produce hydrogen directly from seawater or wastewater with significantly less effort (Tak et al. 2022; International Energy Agency (IEA) 2023). This would eliminate the seawater desalination step an the environmental impact involved. However, current electrolysis membranes are proving to be too sensitive for economic operation with salt water (Tak et al. 2022). For this reason, seawater desalination is currently the most suitable solution for providing high-purity water.

- “Desert Greening” with seawater: seawater desalination can be used to transform desert-like regions into fertile ones and, depending on the location, help to promote food security, biodiversity and economic development. A study by Caldera and Breyer (2023) shows that afforestation projects in the MENA region have the potential to store up to 730 gigatonnes (Gt) of CO_2 by 2100. This corresponds to around 20 times the global CO_2 emissions in 2023 (PIK 2023). In some domestic regions, desalinated water is already used for irrigation, for example in Spain, China and the USA. However, this water does not usually come from the sea, but from locally available saline water resources (Regional Program Energy Security and Climate Change Middle East and North Africa (KAS - REMENA) 2020). Desert greening aims to



irrigate water-poor regions in particular and to build up CO_2 reservoirs alongside agricultural use. However, according to the UN Water Development Report 2014, desalination is not affordable for the poorest, often arid regions, despite falling prices (Voutchkov 2020; Climate-ADAPT 2023). The report describes the high cost of transportation as one of the reasons why water is currently not transported to inland regions on a large scale (United Nations Educational, Scientific and Cultural Organization (UNESCO) 2014). In addition, the disposal of brine and the associated potential contamination of soil and groundwater also pose significant challenges in this regard (El Kharraz 2020; Oron et al. 2023).

Both approaches – hydrogen production and desert greening – illustrate how seawater desalination could open up new avenues in the fight against climate change in the area of climate adaptation and for improved water and energy management. However, they also show the challenges that need to be overcome beforehand, in particular the disposal of the brine, the supply of the desalination plants with renewable energies and economic efficiency.

Conclusion for environmental policy and research

Comprehensive policy and research measures are necessary in order to maximise the benefits of desalination in the future while minimising its environmental and economic drawback. It is also important to integrate various stakeholders into planning processes in order to increase social acceptance. The following section highlights selected fields of action that arise from the context of emerging issues:

- Regulation of brine disposal and promotion of brine utilization: Innovations in desalination must go beyond energy and efficiency discussions and include important developments in the handling of brine and its environmental impact. There is a strong need for regulation, particularly in the disposal of brine, which should take place at different levels. Transparent guidelines and a legal framework for disposal and recycling, for example through international agreements and national laws, as well as the inclusion of circular economy concepts, are urgently needed. Regular monitoring and compliance with strict environmental standards play a key role here. Technologies such as concentrate remediation, which make use of brine as a raw material, should be promoted and further researched in pilot projects. Technical upscaling could also be supported by financial incentives, e.g. for the realisation of long-term demonstrations (Jones et al. 2019).

- Promotion of renewable energies: The high energy requirements of desalination plants are a major challenge. According to the Global Clean Water Desalination Alliance (2015), a total of 218 million tons of CO_2 emissions would be generated per year by 2040 if fossil fuels were used for desalination. The transition to renewable energies is therefore essential for sustainable seawater desalination. This requires further political incentives and research, such as increasing the use of solar cells, improved energy storage solutions and the expansion of off-grid systems (Bundschuh et al. 2021). Assuming that the costs of fossil fuels and CO_2 emissions increase, the transition to renewable energies would also make it possible to reduce costs and address the issue of energy availability.

- Infrastructure expansion: The large-scale use of seawater desalination is primarily a question of economic feasibility and therefore also of global distribution. The vast majority (90%) of seawater desalination takes place in wealthy countries (WeAreWater Foundation n.d.). Infrastructure and energy costs pose the greatest challenge, especially for the poorest, often arid regions (United Nations Educational, Scientific and Cultural Organization (UNESCO) 2014). Here, local saline water sources such as wastewater or brackish water could be used to reduce costs. In regions without alternative water sources, partnerships with coastal areas and investments in infrastructure could be crucial. This enables the distribution of water for drinking water supply and agriculture. In addition, this could be important for future applications such as hydrogen production or desert greening (Asendorpf 2023).

- Integration and adaptation: The decisive factor for a sustainable water supply is the site-specific integration of desalination into a comprehensive water management system that includes water conservation, reuse and innovation. This approach should include, for example, improved cooperation in the water, energy and agricultural sectors and a clear institutional framework for the reuse of brine (PRODES 2010).

Looking to the future, however, seawater desalination should continue to be considered more as an “emergency measure” in the event of water shortages. As a rule, seawater desalination is not only very costly, but also has a strong negative impact on the environment and uses salt water, an abundant but finite resource. Seawater desalination plants should therefore be weighed up comprehensively against possible alternative measures, such as wastewater reuse and water conservation measures, before they are constructed.

2.3 Maritime algae farming

Trend: The fascinating world of algae, ancient organisms that have influenced life on Earth for billions of years, is experiencing a remarkable renaissance. From their beginnings as oxygen producers to their versatility in modern gastronomy, cosmetics and even as a possible substitute for fossil fuels, algae have the potential to play a key role in our sustainable future. This chapter focuses primarily on macroalgae, as most of their use is through aquaculture or collection near the coast, i.e. in interaction with marine areas. Microalgae that can be cultivated in seawater are also considered. The focus is on the following questions: How do macroalgae differ from microalgae? How are they cultivated and used? What opportunities and risks are associated with the establishment and expansion of marine algae production?

Emerging Issues

- Macroalgae on German tables – algae as food
- Health innovations from the sea – macroalgae for the healthcare sector
- Substitution of fossil raw materials with macroalgae – algae as a raw material

In a nutshell

- In this country, algae are better known from Japanese cuisine, as a dietary supplement or as a basic ingredient in natural cosmetics. However, the importance of macroalgae in particular could change significantly in the coming years. Some species have been proven to be very healthy, have a high protein content and can be cultivated close to the coast. Sea vegetables therefore have the potential to make a significant contribution to global food security in the medium and long term. Overall, research results and pioneering companies are demonstrating a wide range of potential applications for macroalgae that go far beyond the markets that have already been developed. However, natural algae stocks are also threatened by climate change. In some regions, tipping points could be reached as early as 2030, leading to a permanent loss of the corresponding ecosystems. In addition, a holistic view is necessary, as further processing steps (post-harvest) can also be associated with environmental disadvantages that can have a negative impact on the overall balance.
- Substituting agricultural goods with algae can easily alleviate the competition for land and reduce the intensive use of soils. This can reduce greenhouse gas emissions and water consumption and protect nature. At the same time, the expansion of maritime algae farming can bind relevant quantities of CO_2 in the long term. On the other hand, exploitation can endanger natural algae stocks and marine biodiversity. Wild collection should therefore be limited and cultivation should avoid negative impacts on the surrounding habitats.

- The interactions between upscaled marine algae farming and the environment are not yet foreseeable and have so far largely been based on estimates. Improved modelling and the establishment of an accompanying monitoring system are therefore necessary conditions. An expansion of marine algae farming must also lead to a reduction in terrestrial agriculture, otherwise the positive environmental potential cannot be realised. Ultimately, consumers and procurers must also be motivated and supported by appropriate (environmental) product labelling in order to develop trust in the as yet little-known algae-based products and to dynamise the market.

Background

Today, algae are mainly known from the beach and the sushi bar. On beach vacations, they spoil the image of crystal-clear water and pristine sandy beaches. In gastronomy, on the other hand, they are increasingly gaining in popularity thanks to Asian cuisine (Costello et al. 2020; Schleuning 2023). Due to their nutrients, they are increasingly being traded as a superfood in Europe. In particular, their ability to bind large quantities of CO_2 is now making them even more important to the public in light of the need to reduce greenhouse gases (Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB (Fraunhofer IGB) n.d.; Faber 2019; Federal Information Center for Agriculture 2023; Bullen et al. 2024).

Algae are very versatile organisms. Biologically speaking, they are not plants. Although they carry out photosynthesis, their structure is much simpler. They can be unicellular or multicellular and have no roots, stems or branches. The diversity of algae species is enormous, but largely unknown. It is estimated to be around 400,000, of which only 175,000 are currently recorded (Demmer and Paál 2023; Guiry and Guiry 2023).

A general distinction is made between macroalgae and microalgae. Macroalgae, known colloquially as seaweed, are multicellular and large enough to be seen with the naked eye. They can grow to several meters in length, are often found in coastal regions and can take various forms (leaf-like, branched, spherical). Within the group of macroalgae, a distinction can be made between various brown algae such as kelp, red algae and green algae. Macroalgae make up about 20% of all algae species (Soler-Vila et al. 2022; Federal Information Center for Agriculture 2023).

Microalgae are a diverse group of microscopic algae that live in various aquatic environments (oceans, lakes, rivers) as well as in humid terrestrial environments. So tiny that one millilitre of water can contain thousands and thousands, they are an important food source for crustaceans, fish and corals, for example (Barsanti and Gualtieri 2018; Yaacob et al. 2022) (Alfred Wegener Institute 2024). Examples of microalgae are *spirulina* and *chlorella*. At around 80%, microalgae make up the majority of all algae species (Icking et al. 2022; Federal Information Center for Agriculture 2023).

Mainly obtained from aquacultures in Asia

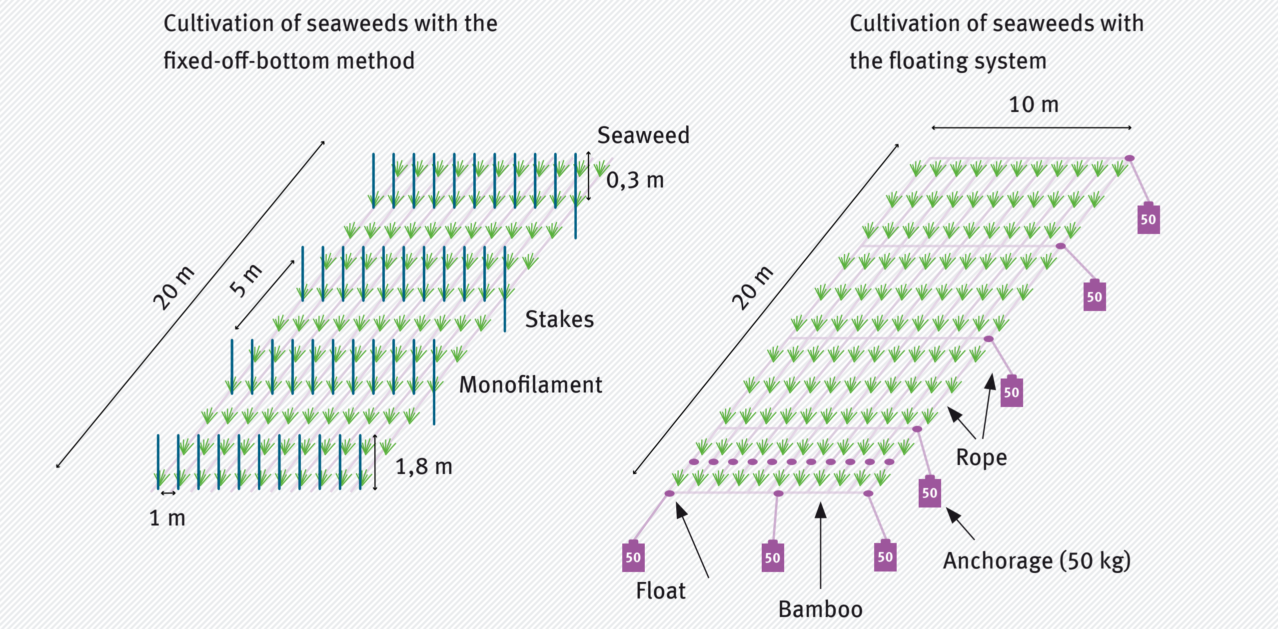
From 1950 to 2019, the cultivation and production of algae increased from 0.5 million tons to 36 million tons. Microalgae have hardly played any role so far. Their share can be put at 0.16%. Worldwide, 97% of macroalgae are produced in aquaculture systems at sea or in artificial tanks on land, with sea production dominating due to its cost efficiency. Tank cultivation allows for better control, but is more expensive and therefore tends to be used only for high-value algae. Only 3% is harvested wild (Federal Information Center for Agriculture 2023).

In the traditional poaching of macroalgae, natural deposits in coastal waters or on the beach are collected by hand. In marine cultivation, the “fixed-off-bottom” method and the “floating system” are the most widespread (see Figure 5; dimensions, depths, materials and mooring weights vary) (United Nations Environment Program (UNEP) 2023).

In the “fixed-off-bottom” method, wooden stakes are fixed to the seabed at regular intervals and in straight rows. Ropes are stretched between the stakes, where algae seedlings – also known as thalli – are fixed about 25 cm apart using a tying technique. The seedlings weigh around 50 to 100 g at the time of planting. With a rope length of 20 m, this method can be

Figure 05

Two main methods for algae cultivation: "fixed-off-bottom-method" and "floating system"



Dimensions, depths, materials, and anchorage weights will vary.
Reproduced from Robledo et al. (2013) with permission.

Source: own representation according to United Nations Environment Programme (UNEP) 2023; p. 5

used to cultivate around 80 young algae per row until harvest.

Raft systems ("floating systems") consist of parallel bamboo poles that are connected with ropes to form a rectangular frame (raft). Floating elements are attached to the edges of the bamboo construction at regular intervals to ensure constant buoyancy. At the same time, the frame is fixed to the seabed with ropes and weights so that the raft system can float continuously just below the surface of the water. As with the "fixed-off-bottom" method, the 50- to 100-g algae seedlings are tied to taut ropes at regular intervals and can grow there until they are harvested (Reef Resilience Network n.d.; Valderrama 2013; United Nations Environment Programme (UNEP) 2023).

Microalgae are cultivated in artificial systems known as photobioreactors. Depending on the species, they require specific water temperatures, sunlight, CO_2 and nutrients such as nitrogen and phosphorus in order to grow. Artificial lighting may be required and the temperature and oxygen content of the water must be regulated (Enzing et al. 2014). When breeding in reactors, a distinction is made between open and closed systems. Open systems are cheaper, but there is a risk of contamination. Sensitive algae are often cultivated in closed systems, where conditions can be better controlled. The cultivation process varies depending on the type of algae and the environment. Once they have grown sufficiently, they are harvested, dried and processed into powder or other products (Enzing et al. 2014; Federal Information Center for Agriculture 2023).

About 85% of algae farming currently takes place in China (20 million tons), Indonesia (10 million tons), South Korea (1.8 million tons) and the Philippines (1.5 million tons). In Europe, less than 1% (290,000 tons) of algae is produced, mainly in Norway, France and Ireland. In contrast to the global trend, around 75% of macroalgae in Europe is obtained from wild stocks and 25% from aquaculture (Icking et al. 2022; Federal Information Center for Agriculture 2023).

Largely unknown all-rounders?

In Germany, algae are mainly known from Asian cuisine – e.g. the red algae nori for sushi and the brown algae wakame in miso soup. Algae are considered a healthy, low-fat food. They provide high-quality proteins, fibre, minerals and vitamin B12, which is otherwise only found in animal products and some edible mushrooms (Uhrig 2020; Fraunhofer-Gesellschaft 2022). However, there are also species that store substances that are unpalatable or even toxic to humans above a certain concentration, such as arsenic. Not all algae are the same and only selected varieties should be included in the diet.

In the health sector, (basic) research is being carried out into the properties of algae in particular. Certain species are rich in important ingredients such as omega-3 fatty acids, minerals and vitamins (Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB (Fraunhofer IGB) n.d.). *Spirulina* and *chlorella* are said to have numerous health-promoting properties, some of which are controversial. Researchers are investigating how algae can help with illnesses. Initial studies by the University of Hohenheim, for example, show that individual species may help heal wounds, inhibit the multiplication of viruses and be effective against cancer cells. Overall, research has shown that proteins, fatty acids and carotenoids from digested microalgae can be easily absorbed by the body. In addition, laboratory tests have shown that many extracts from these microalgae have antiproliferative (inhibiting cell growth), anti-inflammatory and antioxidant effects. In addition, Japanese researchers were able to prove in animal experiments that brown algae products cause breast cancer cells to die. These results are not yet conclusive, but raise hopes that algae could be used to treat cancer and other diseases in the future (Pejic-Pulkowski n.d.; Steiner 2020; Stuhlemmer 2023). Other case studies point to successes in the treatment of asthma, allergies, diabetes and chronic pain. However, these have not yet been confirmed in clinical studies. The actual health-promoting potential is still the subject of basic research (Pejic-Pulkowski n.d.; Icking et al. 2022; Verbraucherzentrale 2023). The high costs of clinical studies and the associated risks have so far meant that algae-based products have not been marketed in the pharmaceutical sector, but rather in the consumer goods sector. Algae and algae components are mainly used in food supplements and cosmetics.

In agriculture, algae are considered an effective and environmentally friendly alternative to synthetic fertilisers (Ammar et al. 2022; Karthik and Jayasri 2023). The Spanish company AlgaEnergy, for example, has been producing so-called biostimulants from microalgae since 2007. The product helps plants to absorb more nutrients such as nitrogen and phosphorus and to become more resistant to environmental stress factors such as weather extremes (AlgaEnergy n.d.).

Algae are also increasingly being discovered as a sustainable resource for meat substitutes. Some species have a protein content of up to 50%, grow very quickly in warm waters and can bind large quantities of CO_2 (1 t of microalgae biomass binds around 1.8 t of CO_2). In addition, no arable land is required to grow microalgae such as *spirulina* (Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB (Fraunhofer IGB) n.d.; Faber 2019; Fraunhofer-Gesellschaft 2022). Algae are already being used to produce vegan foods in Germany. The University of Hohenheim is researching further product potential in cooperation with the Fraunhofer Institute for Interfacial Engineering and Biotechnology (Fraunhofer IGB). A key challenge here is to remove the sometimes very intense and unpleasant fish taste without damaging valuable ingredients (Viva Maris n.d.; BettaF!ish 2022; Stuhlemmer 2023).

Macroalgae-based products for effective environmental and climate protection

Feeding livestock with various macroalgae has been investigated in recent years as a method of reducing methane production. Kinley et al. (2020) concluded, for example, that the methane emissions of cows can be reduced by up to 98% by feeding them with the red alga “Asparagopsis taxiformis”.[17] It also became clear that macroalgae-based feed additives can provide health benefits for livestock - including the reduction of oxidative stress[18] and ketosis.[19] However, there are also safety concerns. For example, ingredients from macroalgae, such as iodine, bromine or arsenic, which are toxic in high concentrations, have been detected in algae-fed dairy cows. The spread of algae as animal feed also poses a challenge for another rea-

17 The red algae contains bioactive substances that block the enzymes of methanogens. Bromoform, the main substance, interrupts the metabolic pathway that normally leads to the formation of methane. This calms the cows’ digestion (Machado et al. 2016).
18 Oxidative stress describes a problematic metabolic state in which the organism produces more harmful free radicals than it can neutralise.
19 Ketosis describes a metabolic state in which the body relies mainly on fat instead of sugar as an energy source. In cows, ketosis can become particularly critical after calving, when milk production increases and a lot of energy is needed.

son: For example – in order to meet the demand for seaweed for the global livestock industry –around 15 million tons of the red algae would have to be made available each year. This would require an enormous increase, as this quantity corresponds to around half of the total cultivation of all seaweed species worldwide. However, as the "miracle algae" *Asparagopsis taxiformis* is only native to and grows in warm coastal regions of the southern hemisphere, this demand is currently far from being met. Research teams are therefore also looking for algae varieties with similar properties in cooler regions such as Ireland (Vijn et al. 2020; Rauner 2022).

Algae are also being considered as a substitute for fossil raw materials (Rodionova et al. 2017). Potential applications range from bricks and flowerpots to handbags and kerosene. This is possible because algae bind CO_2 in the form of glycolate (a precursor of sugar) and lipids (algae oil) as they grow. These raw materials can in turn be used in chemical and biochemical processes to produce starting materials for bio-based plastics, carbon fibres or aviation fuel (Li-Beisson et al. 2019; Stumberger 2020; Demmer and Paál 2023).

In the summer of 2010, a small aircraft powered by algae fuel took off successfully for the first time in Berlin. The world premiere suggested that the biofuel could replace petroleum-based kerosene in the future. In 2019, researchers from Leipzig succeeded in developing a process that enables the production of algae fuel without algae growth. When supplied with carbon dioxide and light, the algae form pure glycolate without gaining biomass. This has significantly increased efficiency. The yield potential of biofuel from algae is now around twice as high as from maize and can potentially be optimised even further. Nevertheless, algae-based kerosene is significantly more expensive than conventional (Faber 2019; Taubert et al. 2019). According to Prof. Dr. Brück from the Technical University of Munich, a large algae cultivation plant with a connected refinery would require investments in the hundreds of millions (Steiner 2020). Despite the existing challenges, algae could play an important role on the road to more climate-friendly aviation. Intensive research is being conducted into solutions and biofuels are considered to have great potential to make a significant contribution (Hungerland et al. 2024).

Major growth potential in Europe

As already explained, the majority of algae farming currently takes place in Asia. China, Indonesia, South Korea and the Philippines are the big players with a strong focus on macroalgae in aquaculture. Asia currently covers around 99% of the market (Food and Agriculture Organization of the United Nations (FAO) 2020b; Vincent et al. 2020). According to the Food and Agriculture Organization of the United Nations, the global macroalgae market more than tripled between 2000 and 2018. In the years that followed, the cultivation of algae increased at a slower but steady pace. In 2020, a global growth rate of 1.4% was recorded, which corresponds to half a million tons (Food and Agriculture Organization of the United Nations (FAO) n.d.; Food and Agriculture Organization of the United Nations (FAO) 2020b). Overall, there is a consensus that the industry will continue to grow globally (Food and Agriculture Organization of the United Nations (FAO) n.d.; Ferdouse et al. 2018; Food and Agriculture Organization of the United Nations (FAO) 2020b; Fortune Business Insights 2021; Grand View Research 2021).

The Seaweed for Europe association estimates the growth potential of maritime algae farming in Europe at EUR 9.3 billion by 2030, with 30% of this market being covered by companies within the European Union. This could create between 85,000 and 115,000 jobs and reduce greenhouse gas emissions by up to 5.4 million tons annually by binding CO_2 in algae (Norwegian Seaweed Association n.d.; Vincent et al. 2020). Seaweed currently ranks 6th among the preferred plant-based meat substitutes in Germany (Statista GmbH 2022). The increasing emergence of start-ups shows that the seaweed industry is picking up speed in Germany and Europe (The Seaweed Company n.d.; Viva Maris n.d.; BettaF!ish 2022; Alfred Wegener Institute (AWI) 2023).

In Norway in particular, the seaweed sector has experienced a great deal of political and entrepreneurial hype in recent years. With its numerous fjords, the country has ideal natural conditions for seaweed cultivation. The government and industry recognised the potential of marine algae farming for Norway at an early stage, identified the sector as a future field as part of its sustainability strategy (Blue Growth strategy) and strategically promoted it. The first cultivation license was issued in 2014 and important expertise in algae cultivation has been built up since then. By

2022, the number of licenses had risen to 511, spread across more than 100 production sites (BusinessPortal Norway 2020; Albrecht 2023a). There are already 23 companies active in Norwegian algae production. This rapid development, combined with estimated growth potential of 4 megatons by 2030 and 20 megatons by 2050, has created a gold-rush atmosphere: seaweed is considered *green gold* and algae farmers are seen as key players in a *multi-billion-dollar market* (Albrecht 2023a).

Well-known German organisations are also helping to shape the expanding industry: For example, the company MACROCARBON SL was launched in the Canary Islands in spring 2023. The start-up was created as a spin-off of the Helmholtz Center for Ocean Research Kiel and the young company Carbonwave, with the support of the chemical group BASF. MACROCARBON SL aims to produce biological carbon raw materials for the chemical industry from free-floating macroalgae (Alfred Wegener Institute (AWI) 2023).

Critical observers of the emerging algae farming industry in Europe are warning that marine ecosystems must not be overstretched. With the EU Commission's communication "Towards a strong and sustainable algae sector in the EU" (European Commission (EC) 2022) and the Strategic Guidelines for a more sustainable aquaculture referenced therein provide orientation points at EU level. Convincing strategies for the sustainable use of this valuable marine resource are still lacking at national level. Stefan Kraan, marine biologist and former president of the International Seaweed Association, therefore recommends that the harvesting of wild algae stocks on a large scale should be strictly regulated. Wild algae are not only a CO_2 sink, but also an important habitat and pillar of biodiversity. A stronger focus on aquaculture based on the Asian model could be a solution. Global algae stocks would remain secure, while the controlled cultivation of macroalgae would meet market demand (Food and Agriculture Organization of the United Nations (FAO) n.d.; Vincent et al. 2020; Rauner 2022).

With a view to the environmental impact of these developments, the following Emerging Issues section addresses the following questions:

1. Does algae farming actually reduce the burden on the environment and biodiversity or does it merely shift the negative effects from the terrestrial to the marine aquatic environment?
2. What open research needs exist and what control options are already available or need to be developed further?
3. Should an expansion of marine algae production be supported or viewed with skepticism?

Emerging Issues

There are sufficient drivers for the development of marine algae farming. Resource consumption in general will continue to increase massively due to economic and demographic growth (Organization for Economic Co-operation and Development (OECD) 2019). Algae, and macroalgae in particular, offer great potential to curb the associated increase in land consumption and intensification on land resulting from the increased demand for agriculturally produced goods and to protect the climate (Spillias et al. 2023; United Nations Environment Programme (UNEP) 2023). They can substitute food from traditional agriculture (see Emerging Issue 1), supply products for medical and cosmetic use (see Emerging Issue 2) and replace fossil and regenerative raw materials from agriculture (see Emerging Issue 3).

On the one hand, macroalgae have great mitigation potential for combating climate change (United Nations Environment Programme (UNEP) 2023). On the other hand, their natural occurrences, in the form of kelp forests[20], are themselves severely threatened by global climate change: in some regions, tipping points could be reached in the 2030s that could lead to a permanent loss of these ecosystems (Lenton et al. 2023). In addition to abiotic factors such as maritime heatwaves, sea urchins in particular are drivers of this change and can also permanently prevent regrowth – resulting in desolation.

Spillias et al. (2023) have calculated the availability of marine cultivation areas for seaweed (for different types of seaweed with different uses) and developed different types of scenarios up to 2050 that assume greater demand in order to derive environmental impacts. The scenarios consider food, feed and fuel[21] as

20 Kelp forests are mostly coastal natural ecosystems that are often characterised by a dense growth of brown algae. They occur in the Pacific as well as in the Atlantic and Indian Oceans. In Europe, they can be found in the North Sea and parts of the Baltic Sea.
21 In the scenario, 10 % of human nutrition, 10 % of animal nutrition and 50 % of biomass energy is replaced by seaweed.

well as an overarching scenario and a specific feed scenario with the red algae *Asparagopsis* as an additive for ruminant feed. It is often not possible to strictly separate the environmental impacts according to different fields of application, as the production methods and the algae species used are the same. This means that globally significant reductions in greenhouse gas emissions are possible across the various fields of application. There could also be savings in the use of nitrogen fertilisers in agriculture and in water consumption. However, there is also a risk of rebound effects due to the greater supply, as agricultural land could be renaturalised or used less intensively, but this cannot necessarily be expected without control.

In principle, there are also suitable areas in European waters and, as described above, these are currently being developed more intensively, particularly in Northern Europe. However, there are always conflicts of use with other forms of management, such as energy generation in offshore wind farms. Although these are generally well suited for multi-use applications with macroalgae cultivation, various lines of conflict arise here. These include unresolved issues relating to liability and responsibility or the assumption of higher insurance premiums. The effects on biodiversity are also unclear. Both forms of cultivation are an intervention in nature and can contribute to the spread of invasive species, both individually and in combination, by serving as stepping stones for these species due to their solid surfaces. The question therefore arises as to which actor must take countermeasures or compensatory measures. These projects ultimately fail in their implementation due to such open questions of risk governance (van den Burg et al. 2020). However, there are also examples that point in a more positive direction. For example, kelp farms established in temperate waters have proven to be positive for biodiversity (United Nations Environment Programme (UNEP) 2023). However, compared to unmanaged kelp forests, species diversity is lower here. A water quality-improving effect has also been demonstrated for macroalgae (Sudhakar et al. 2018; van den Burg et al. 2020; United Nations Environment Programme (UNEP) 2023) such as better aeration of water bodies, binding of heavy metals or lower acidity. Macroalgae also contribute to coastal protection.

This is an important quality that could further boost the cultivation of macroalgae. The ecosystem service of CO_2 sequestration or the reduction of eutrophication, which could also be remunerated in monetary terms as a compensation measure, could represent additional business for those involved in marine algae farming. However, the magnitude of this effect and the fundamental environmental risks have not yet been sufficiently researched (Ross et al. 2023). There are also indications that organic carbon is removed from the carbon cycle in dissolved or sedimented form in the long term during the cultivation phase, regardless of the subsequent use of the macroalgae (Gao et al. 2022).

1. Macroalgae on German tables – algae as food

Algae have been cultivated as food for thousands of years (Diaz et al. 2023). The high content of important nutrients makes them a possible solution to meet the constantly growing global demand for food (Diaz et al. 2023; Spillias et al. 2023). While they are traditionally on the menu in Asian countries in particular, they have also increasingly found their way onto plates in Europe in recent years. However, they are currently mainly used here as superfoods and dietary supplements. In order to be used as a wholesome food in Europe and many other countries, acceptance among the population and knowledge about the preparation of algae as a staple food must be increased (Kind 2022; Spillias et al. 2023). If this step is successful, according to a study by Spillias et al. (2023) algae have as much potential as corn or wheat once did to satisfy the hunger of the world's constantly growing population. However, one major challenge is consumer acceptance, which is affected by the "fishy" taste, among other things (Onwezen et al. 2021; Mellor et al. 2022).

A total of 6.5 million km^2 of ocean area is globally suitable as a cultivation area for macroalgae (Spillias et al. 2023). Using this area could reduce the pressure on (potentially) productive areas on land. Macroalgae can store CO_2 and their cultivation requires fewer greenhouse gas-relevant inputs, as fertilisation can usually be dispensed with (Spillias et al. 2023). The classic problems of terrestrial agriculture, such as erosion of the upper soil layers, consumption of fresh water, disruption of nutrient cycles and pollution of surface and groundwater, can be avoided with algae cultivation: This is potentially a relief for the environment.

Current challenges exist in researching the effects of algae monocultures on marine ecosystems. Relevant factors include shading, absorption of nutrients, reduction of kinetic wave energy, new habitat for diseases, parasites and other organisms, or the introduction of invasive species (Campbell et al. 2019). In particular, the impact of marine algae production sites on marine mammals needs to be investigated. Research groups in Norway and the USA, among others, are currently investigating the benefits and risks of algae farms (Kind 2022). It is always important to take a holistic approach that considers not only production, but also the entire life cycle. For example, a life cycle assessment of kelp grown in Norway as a source of protein for animal husbandry did not show any advantages over soy from Brazil in terms of climate impact in most of the scenarios used (Koesling et al. (2021). An important reason for this was the high energy input during drying. On the other hand, Wu et al. (2023) show the environmental benefits of algae-based products and their terrestrial counterparts from breeding to cultivation and processing in their comparative life cycle assessment.

Uncertainties remain in the use of nanotechnology and the modification of algae. Nanotechnology can be used to improve the growth conditions of macroalgae and protect against bacterial infestation and biofilm formation. However, the risks to humans and the environment have not been clarified (Khan et al. 2023). Only a few accredited laboratories and pilot plants within the EU use genetic engineering to modify algae. However, open-water experiments with genetically modified algae are already taking place in the USA (California) and Mexico (Khan et al. 2023). The potential impact of this technology is therefore rarely discussed. On the other hand, genetic depletion in wild algae species induced by cultivated algae is a documented risk (Valero et al. 2017).

2. Health innovations from the sea – algae for the health sector

Algae are an interesting starting material for the pharmaceutical and cosmetics industries. The reason for this is the high density of bacteria on their surfaces and the diverse bioreactive substances produced as a result. These active algae substances can effectively inhibit the growth of human pathogens. Viral inhibition and protection against UV-B radiation have also been observed. Tannins have also been identified in bladderwrack that have an anti-carcinogenic effect (Catarino et al. 2021). Small quantities of macroalgae have therefore been harvested from wild stocks for the pharmaceutical and cosmetics industries for some time. However, production chains that rely on the cultivation of algae are now also being established in order to scale up the quantities. Maritime regions that are located in the temperate zone are increasingly being developed (Chauton et al. 2021). The cultivation of algae for the health sector is proving successful, although this can lead to a reduction in the active ingredients (Vega et al. 2020).

The environmental impact of wild harvesting for the cosmetic and pharmaceutical sectors is only rarely addressed in the literature. In principle, the consequences and dangers of overexploitation of algae stocks by certain harvesting techniques are pointed out (Mac Monagail et al. 2017). Specifically, these are mechanised "clearing techniques" of standing algae stocks. It is generally recommended that only certain species, such as red algae, which grow back quickly and have stable populations, should be removed (Cotas et al. 2024). Collection on beaches after storm events is not considered problematic. In Asia, algae cultivation for the pharmaceutical industry is the common method for extracting the active ingredients (Mac Monagail et al. 2017) as high selectivity is important here, which can only be achieved to a limited extent with wild collection.

Cultivation in the pharmaceutical and cosmetic sectors poses similar environmental risks to those in the food sector, as some of the species involved are the same. However, it appears that integrated multitrophic cultivation is generally suitable despite some limitations (Vega et al. 2020). In direct comparison with conventional pharmaceutical products, macroalgae-based alternatives have an environmental advantage (Pereira and Cotas 2024). Processes with a reduced environmental impact can also be used to extract the active ingredients (Pereira and Cotas 2024).

However, scaling up the cultivation of macroalgae also increases the risks to biodiversity and the spread of invasive species. Intact biodiversity plays a decisive role in the emerging issue of health innovations from the sea. There is still a great need for research into the identification and safeguarding of potential active ingredients (Chauton et al. 2021). With the ongoing loss of species, the potential could be significantly reduced without even being precisely known.

3. Substitution of fossil raw materials with macroalgae – algae as a raw material

The global search for sustainable alternatives to fossil fuels has increasingly focused attention on renewable resources in recent years. In this context, macroalgae are coming into focus as a promising alternative. These marine plants offer enormous potential as a source of energy and of chemical raw materials.

Macroalgae can be converted into biogas or biomethane through fermentation or thermochemical processes. The resulting biogases can be used to generate electricity or as fuel for vehicles, which could theoretically make an important contribution to reducing dependence on fossil fuels (Zhao et al. 2022).

The higher productivity per unit area compared to the extraction of plant-based raw materials on land and the possibility of producing in areas that do not compete with food production or nature conservation on land also help to reduce undesirable side effects of biofuels (Schröter-Schlaack and Aicher 2019). However, it should be noted that there is also competition for land in coastal/marine areas with areas under nature conservation.

Compared to fuels from fossil raw materials, a favourable greenhouse gas balance is to be expected, as it is a closed CO_2 cycle and climate-damaging land use changes are not to be expected (Schröter-Schlaack and Aicher 2019). However, a problematic side effect of replacing biomass produced on land may be that certain co-products, such as fermentation residues, are no longer produced and must then be replaced by primary products (Spillias et al. 2023).

In addition, biofuel production from macroalgae poses challenges such as the scalability of algae cultivation, water use in biorefineries, the availability of raw materials and the regulation and licensing of biorefinery plants (V et al. 2021). The biological diversity of algae and seasonal fluctuations in their composition must also be taken into account (Zhang et al. 2022).

Large macroalgae are also suitable for the chemical industry, as they contain valuable chemical compo-

nents that can be used as raw materials for the production of chemicals. Polysaccharides, proteins and lipids are the main components of macroalgae and can be obtained using various extraction and processing methods. Macroalgae therefore represent a promising raw material for the production of bioplastics. Even though the production of algae-based plastics is still in its infancy (Mouritsen et al. 2021), there are already numerous studies in various fields of application that confirm their fundamental suitability as a material. For example, they are particularly durable and heat-resistant (Mouritsen et al. 2021). In terms of raw material extraction and greenhouse gas balance, the bioplastics obtained can represent a more environmentally friendly alternative to petro-based plastics or plastics derived from land biomass (Sudhakar et al. 2024). Other environmental issues, such as disposal-related problems or the formation of microplastics, remain.

Conclusion for environmental policy and research

There are three major issues that potentially need to be researched and managed. These include the reduction of direct effects, the avoidance of rebound effects and the strengthening of demand.

Reduction of direct impacts: An expansion of algae farming, particularly with regard to associated approval procedures, must be accompanied by modelling (in advance) and monitoring (during operation). This is necessary in order to be able to assess both site-specific and far-reaching impacts of macroalgae farms and restrict the corresponding approvals. In concrete terms, this would mean observing changes in the genetic composition of the adjacent natural algae populations and other changes in the ecosystem, including in the megafauna. In general, all changes in biodiversity must be considered. This applies in particular to the use of certain locally atypical species. Since the cultivation areas are managed in different ways by different stakeholders, especially in the case of potentially recommendable multi-use forms, the relevant authorities[22] must set up cross-stakeholder processes to clarify questions of responsibility there (van den Burg et al. 2020). For example, a risk assessment process that integrates all forms of use should be set up at the outset. In addi-

22 The competent authorities for marine aquaculture include water and shipping authorities, nature conservation authorities and fisheries authorities.

tion to data-based analyses, this should also include stakeholder consultations with the affected actors. A round table can also accompany such processes in the longer term and ensure transparent external communication. Regulation of the harvesting of wild stocks of the algae species used should also be examined.

Avoidance of rebound effects: Rebound effects and oversupply resulting from the simultaneous cultivation of marine and terrestrial agricultural goods must be addressed. The greater supply can lead to lower prices and thus also to higher demand. The introduction of algae farming must also lead to a de facto reduction in the pressure on terrestrial areas. As these effects are not clear, they should be substantiated with the help of modelling, e.g. GLOBIOM[23], and corresponding research should be set up by the Environment Department. These are merely a building block for initiating countermeasures. At the same time, appropriate incentives should therefore be created that result in a reduction in land use. Farmers should also be involved and trained in this transformation process so that this can also be achieved in a socially responsible manner. Even if – see Emerging Issue 1 –positive climate impacts are currently uncertain, the benefit of replacing animal feed with algae-based products, for example, would be obvious. An integrated cross-departmental strategy should therefore be developed that considers terrestrial and maritime agriculture. Although the German government's bioeconomy strategy also takes algae into account, it does not contain sufficient approaches for exnovation – i.e. for reducing intensive agriculture.

Strengthening demand: As with many other substitution products, visible information for consumers is also key for products based on macroalgae. It is particularly important to educate both consumers and companies about how macroalgae-based products can effectively contribute to environmental and climate protection. This information should clarify the connections between their own actions and possible positive effects on aquatic biodiversity. The topic of (environmental) labelling should also be addressed, as it should better identify algae-based products according to their environmental benefits and exclude environmentally harmful production methods. Clear labelling is also necessary to include algae-based products in sustainable (public) procurement. Accordingly, the range of products must be on the market and expanded. The production of raw materials and their further processing should be increased through incentive measures, such as tax concessions, in order to satisfy the existing demand within the EU. As outlined in the EU communication "Towards a strong and sustainable algae sector in the EU" (European Commission (EC) 2022), market entry should be made easier for small and medium-sized enterprises (SMEs) in particular, while manufacturers of foodstuffs, cosmetics, etc. should also be made aware of the potential substitution or use of algae. Public welfare-oriented models such as solidarity agriculture should also represent a form of business for the maritime algae industry and be promoted accordingly. Tax concessions on algae products can also make them more competitive on the market (Duarte et al. 2022).

23 Global Biosphere Management Model – a model to study the interactions between competing land uses (agriculture, forestry and biomass cultivation and modules for fisheries and aquaculture).

2.4 Democracy in danger?

Trend: Anti-democratic developments jeopardise democratic systems in both national and international contexts. The political development of societies is in flux and is strongly linked to past, present and future crises. Against the backdrop of this trend and the overall volatile global political situation characterised by polycrises, the 2024 "super election" year is of particular importance. A total of around 4 billion people will vote in 76 countries. What impact will anti-democratic developments, and in particular the spread of disinformation, have on environmental, nature and climate protection efforts at both national and international level?

Emerging Issues

- Democracies in a crisis of confidence
- Increase in anti-democratic tendencies within Germany
- Increasing strengthening of autocracies internationally

In a nutshell

- Social developments that threaten democratic systems can be observed around the world. While the number of autocratic regimes is on the rise, democratic values and institutions are coming under increasing pressure. This trend has an impact on environmental and transformation policy, as the tendency towards autocratisation intensifies ideological conflicts and makes international cooperation to overcome multiple crises, including the transformation towards climate neutrality, more difficult.

- The strengthening of anti-democratic forces in Germany and their increasing influence at municipal and state level jeopardise further progress in national environmental policy.

- The deliberate spread of climate change disinformation poses a serious threat that undermines public support for environmental action, as well as trust in democracies in general. A significant number of right-wing populist parties in Europe are sceptical of the scientific consensus on man-made climate change. Parties such as the German AfD, the UK's UKIP, the Dutch Party for Freedom and the Danish People's Party actively challenge the scientific evidence and spread disinformation.

- In view of the threat posed to important sustainability goals by autocratic regimes and actors, environmental policy must be able to prevent and counter disinformation in a targeted and effective manner, be it through the regulation of corresponding platforms or the promotion of information campaigns and fact-checking services. In the European Union's (EU) domestic sphere of influence, models of civic participation

> and involvement in projects related to sustainability and nature conservation can also help to strengthen the democratic foundations of environmental protection.

Background

In the period from 2017 to 2023, both the proportion of autocracies and the proportion of complete democracies increased. This was due to the fact that incomplete democracies have become more democratic and hybrid regimes more authoritarian. Overall, however, the proportion of democratic states is significantly lower. In 2023, 74 states in the global community were democracies with a share of the global population of 45.4%. In contrast, 93 states with a global population share of 54.6% were classified as hybrid or authoritarian regimes according to the Democracy Index of the Economist Intelligence Unit (EIU) for 2023.

In times of global crises, authoritarian actors promise seemingly simple answers to the complicated questions of the present. Authoritarian rulers are systemically dismantling democratic structures. Although a few countries, such as Poland in 2023, have seen a shift in power towards liberal parties as a result of elections, given the developments of recent years (see Figure 7), it is unlikely that basic democratic values will be strengthened worldwide in the coming decades.

The rise of anti-globalist populism and climate-sceptic politicians is seen as a significant threat to climate policy, as it weakens multilateral cooperation and undermines environmental protection efforts. With the increasing need for broad issue-based coalitions in the European Parliament, there are also growing concerns about the legitimisation of right-wing populist positions (Schaller and Carius 2019). The increasing presence of climate-sceptic parties in European governments makes ambitious climate policy proposals more difficult and presents the international community with the challenge of continuing effective cooperation.

Characteristics of democratic structures worldwide

Based on the Economist Intelligence Unit's (EIU) Democracy Index, countries have been rated since 2006 according to the effectiveness of their democratic structures (see Figure 6). The degree of democracy is assessed on the basis of expert assessments and other data sources, such as public opinion surveys (World Values Survey and Eurobarometer), in the categories of electoral process, pluralism, functioning of government, political participation, political culture and civil liberties. It should be noted here that a Western-style ideal model of democracy is used as the benchmark for the assessment. According to a points system with a scale from 0 to 10, the countries are classified as follows (Kekic 2007):

Full democracies (8 - 10 points) are states in which civil liberties and fundamental political rights are respected and strengthened by an inclusive political culture. They are characterised by effective government control, an independent judiciary, functioning governments and a diverse and independent media landscape.

Incomplete democracies (6 - 7.99) exhibit isolated democratic deficiencies, for example in the context of an underdeveloped political culture or low political participation. Although elections are fair and free and basic civil liberties are granted, violations of press freedom, minor repression of political opposition or problems with governance may occur.

Hybrid regimes (4 - 5.99) are states with pronounced shortcomings, such as an underdeveloped political culture, low political participation and deficits in governance and the rule of law. In these countries, the government often exerts pressure on the political opposition, fraudulent elections prevent fair and free elections, the judiciary is not independent, corruption is widespread and freedom of the press is not guaranteed.

Authoritarian regimes (0 - 3.99) are often absolute monarchies or dictatorships without any political pluralism. Their institutions have only limited democratic structures and the judiciary is not independent. Violations of civil liberties are common, elections either do not take place at all or are manipulated, the media are under state control and there is a culture of repression and criminal prosecution of government criticism.

Over the past decade, the global trend towards autocratisation can be traced on the basis of the EIU's analysis results. The changes are nominally small, but over the years have been steadily to the disadvantage of democratic forms of government (see Figure 7).

Creeping autocratisation

In an overall assessment of the changes in democratic systems in the countries examined worldwide, it must be concluded that regimes are becoming more autocratic. Developments in countries such as Russia, Turkey, Hungary and Poland are characterised by persistent and significant declines in democratic characteristics (March 2023). Looking at the past ten years, it is clear that autocracies are becoming increasingly entrenched. The decline in democratic pillars particularly affects the enforcement of civil liberties, such as freedom of the press and the principles of the rule of law. The year 2024, which is being referred to as a "super election" year because more elections than ever before are taking place worldwide within one year,[24] is considered a particular challenge for the further development of social cohesion and political culture (Shafy 2024).

Climate and environmental protection policy in the context of democracies and autocratic systems

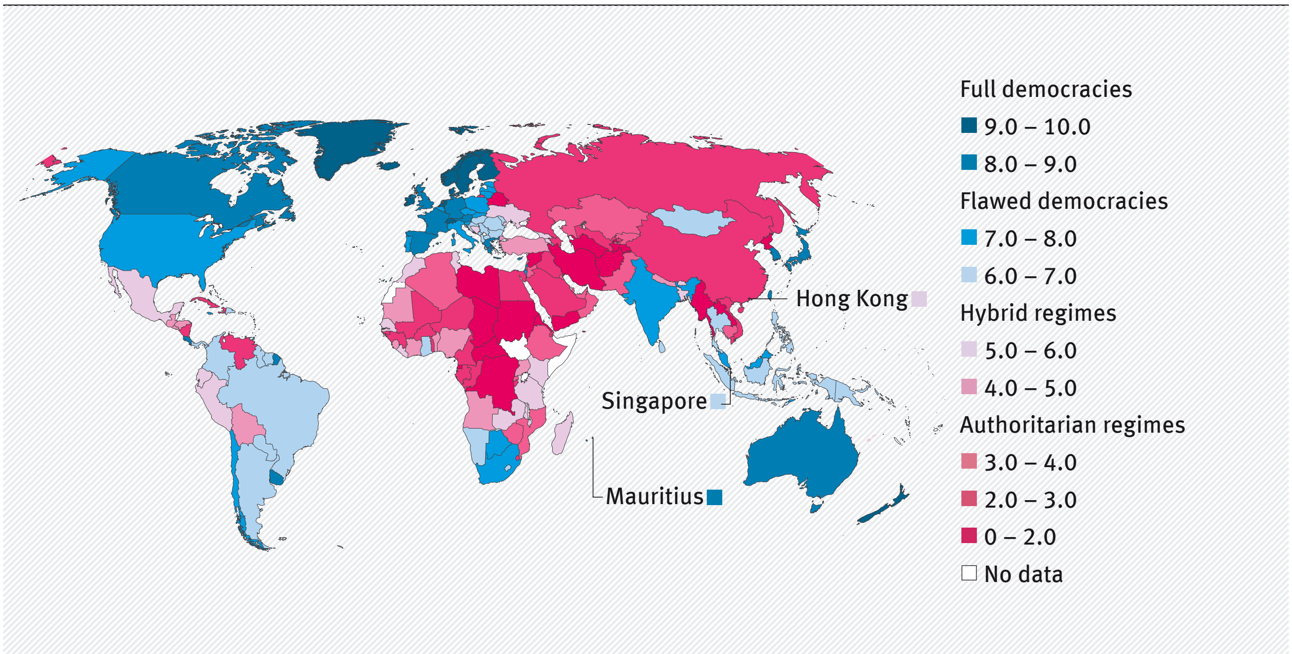
Neither established democracies nor authoritarian states achieve their national climate protection targets. The form of government is not an indication of adequate climate protection policy per se, as the comparison of the EIU's Democracy Index (see Figure 6) and the Climate Action Tracker (see Figure 8) shows. Nevertheless, good and reliable international relations are just as important as the population's trust in the government in order to achieve sustainable implementation of climate and environmental protection measures. The environmental movement has always been characterised by protests by the civilian population. The right to demonstrate, freedom of expression and diversity of the press are of key importance for climate and environmental policy. In autocracies, these rights are restricted. As a result, societies lack an important lever for effective climate and environmental protection policy (Eitze et al. 2020).

While activists in democratic countries have in recent years successfully contested climate and environmental protection lawsuits in national courts and

Figure 06

World map by regime type; as of 2023

Democracy Index 2023, global map by regime type

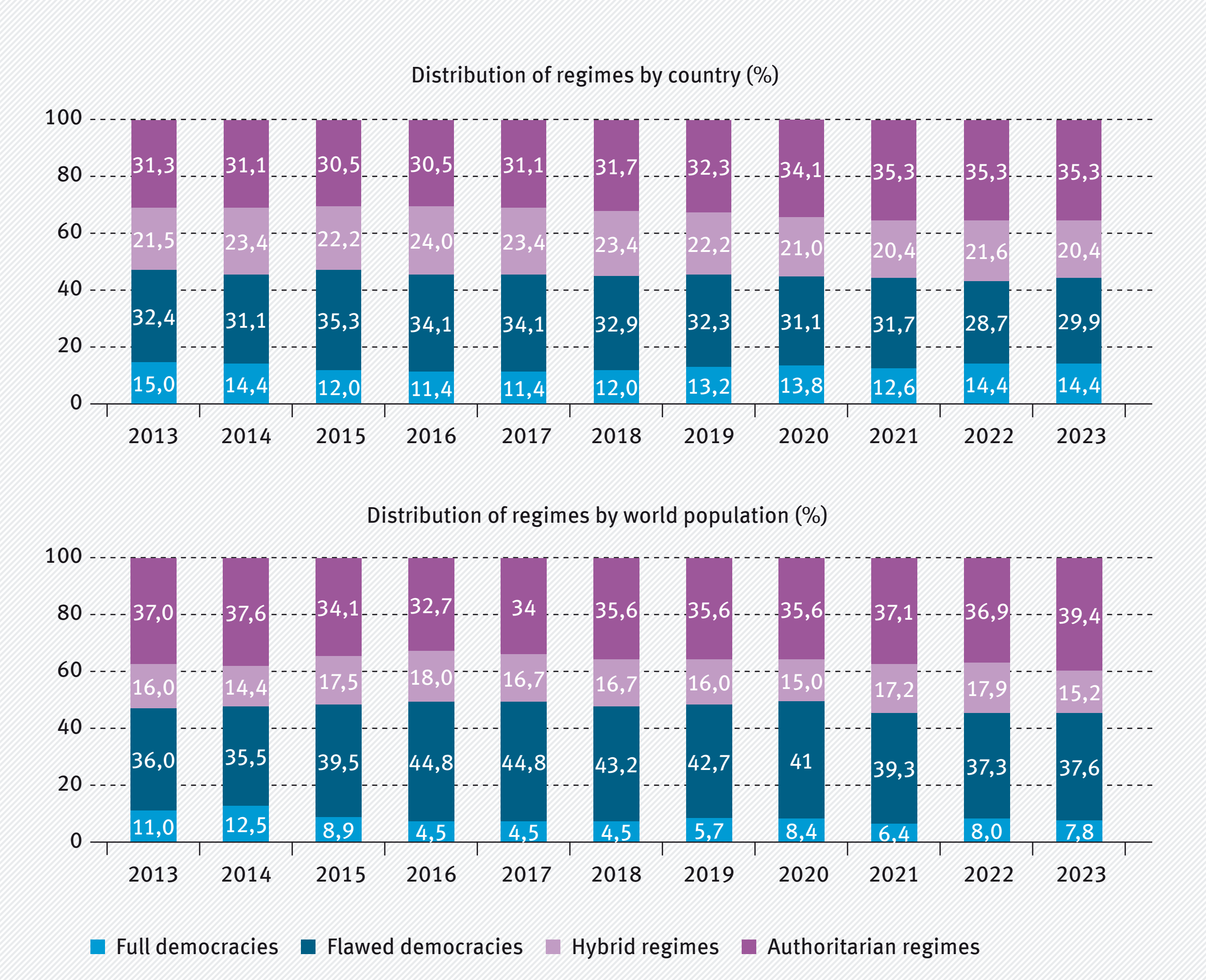


Source: own representation according to (Economist Intelligence Unit (EIU) 2024)

24 Around half of the world's population will be called upon to vote in 70 elections: These include the European Parliament elections in June 2024, the state and local elections in the eastern German states in autumn 2024 and, at international level, the national elections in Russia (March 2024) and the United States (November 2024) (Federal Government 2024).

Figure 07

Global distribution of regime types by country and world population



Note: The 'world population' refers to the population of the 167 countries covered by the index. As only microstates are excluded here, this corresponds to almost the entire estimated world population.

Source: own representation according to (Economist Intelligence Unit (EIU) 2014; Economist Intelligence Unit (EIU) 2015; Economist Intelligence Unit (EIU) 2016; Economist Intelligence Unit (EIU) 2017; Economist Intelligence Unit (EIU) 2018; Economist Intelligence Unit (EIU) 2019; Economist Intelligence Unit (EIU) 2020; Economist Intelligence Unit (EIU) 2021; Economist Intelligence Unit (EIU) 2022; Economist Intelligence Unit (EIU) 2023; Economist Intelligence Unit (EIU) 2024)

most recently before the European Court of Human Rights, climate and environmental protection activists in hybrid and authoritarian regimes are sometimes not only prosecuted but also killed. The prosecution of climate activists in Western democracies is a new development (Climate Rights International (CRI) 2024). The ability to legally assert oneself as a group or individual against the state is an essential advantage of democracies over autocracies (Nitsche 2024). Moreover, in democracies, environmental and climate protection measures are initiated at various decision-making levels within the framework of the respective political system. This multi-level policy results in a variety of measures and projects that, influenced by the innovative power of democratic societies, lead to a more well-founded climate and environmental protection policy (Gross 2023).

Looking to the future

Sovereignty, competition and economic growth are all coming under pressure as a result of climate change. Whether and how it will be possible to find new forms of political action that are up to the challenges remains to be seen. What is clear, however, is that climate change presents political decision-makers with enormous tasks (Wainwright and Mann 2020). In view of the development of political systems and societies, which underlines the anti-democratisation trend of the global community, the following futures were derived. Against the backdrop of the unknown political landscape after the 2024 and 2025 elections, they describe possible development paths that should provide orientation for political decision-makers.

- Democratic states are strengthening their cooperation to protect the environment and nature, defend human rights and consistently implement sustainable transformation. The governments of democratic states are fighting side by side against political polarisation, fragmentation, disinformation and attacks on national sovereignty. Their joint efforts are aimed at strengthening democratic resilience, protecting human rights and reducing CO_2 emissions.

- Anti-democratic forces are making gains in the 2024 elections. Democracies are threatened by disinformation, populism, political polarisation and social unrest. National governments focus on economic growth for their own country and disregard both international climate protection agreements and the Human Rights Charter. In the years that follow, more incomplete democracies become hybrid regimes. Citizens lose trust in democratic institutions and processes.

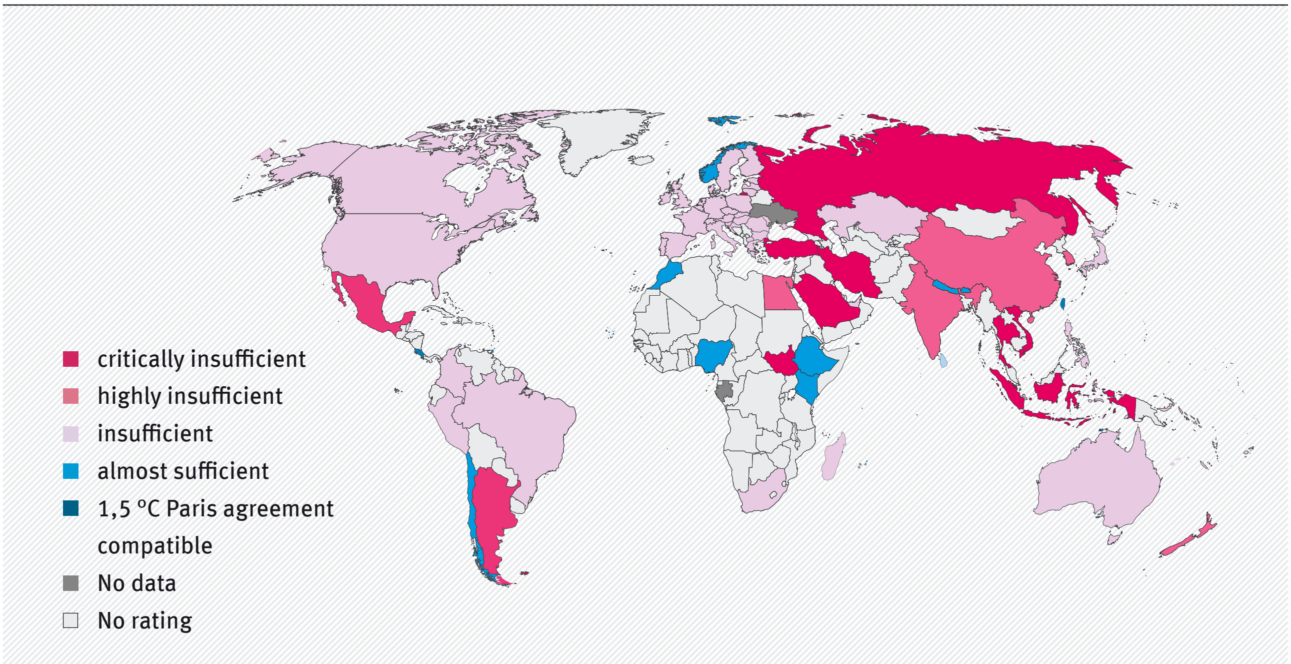
- International cooperation is characterised by mistrust and unreliability. The number of autocracies continues to increase worldwide. Intergovernmental cooperation does not pursue goals of solidarity, but national economic interests. The vision of a global community cooperating on the basis of shared fundamental values still exists among the strong democracies. The effective pursuit of common goals to preserve the basis of life requires a willingness for international rapprochement and a critical examination of the various interests.

In addition to the question of how (environmental) policy should react to the possible developments outlined above, the following Emerging Issues section is also dedicated to answering the following questions:

1. How do disinformation campaigns affect trust in democratic processes and what measures can be taken to restore trust in democracies?
2. How does the rise of populist parties, especially the AfD, influence changes in the decision-

Figure 08

Illustration of the effects of climate measures taken by various governments to achieve the Paris Agreement using the Climate Action Tracker (CAT)



Source: own representation according to Climate Action Tracker (2024)

making structures of environmental and climate policy in Germany?
3. How does the worldwide rise of autocracies affect the international community's ability to respond effectively to global environmental and climate challenges?

Emerging Issues

The decline in trust in political institutions and public bodies in Western societies, increasing autocratisation and the rise of populist movements are significant trends that are putting pressure on democratically governed states and jeopardising the stability of democratic institutions. The scope of these changes is particularly relevant when it comes to tackling global and supra-regional challenges, such as climate policy or supra-regional environmental policy issues. The effectiveness of the implementation of environmental policy measures is directly linked to political stability and the quality of democratic processes (Cohen 2021).

1. Democracies in a crisis of confidence

Studies by the Friedrich-Ebert-Stiftung (2019), the Körber Foundation (2023) and the Eurobarometer (2023) show a significant decline in trust in political decision-makers, governments and parties, exacerbated by socio-economic tensions and the rise of populist movements. In Germany in particular, the Körber Foundation (2023) shows that 54% of respondents are sceptical about democratic institutions –a trend that is also reflected at European level in expressions of distrust in parliaments, parties and the judicial system (European Commission 2023).

The "Citizens' survey of public services" (2023) shows that only 27% of respondents currently trust the state to manage its many tasks effectively – a significant decline since 2020. The majority of respondents feel that the state is overburdened with challenges in the areas of asylum, education, environmental and climate protection, healthcare and social justice. In addition, 56% would like to see more decisive leaders in politics, while 71% feel that politicians are out of touch with the everyday realities of the population (Körber Foundation 2023). This perceived distance also reduces confidence in the ability of political decision-makers to implement effective environmental protection measures and weakens the motivation to engage in climate and environmental protection, especially among those who feel unheard (Kulin and Sevä 2020).

At the same time, disinformation campaigns, partly controlled by autocracies from abroad, partly controlled by domestic anti-democratic forces, are manipulating public discourse, driving the loss of trust described above and influencing political decisions (CAAD 2023). Events such as Brexit and the 2016 US presidential election illustrate how the spread of false information via social media undermines trust in democratic processes and deliberately influences political outcomes (Wolling et al. 2023). These campaigns, which deliberately spread misinformation, differ from unintentional misinformation in their clear aim to deceive and manipulate, as well as to control the flow of information in order to influence public opinion and discredit political opponents (Ruttloff et al. 2023).

Climate Action Against Disinformation (CAAD) and the Institute for Strategic Dialogue (ISD) have documented how climate disinformation is specifically used to weaken environmental and climate policies. Right-wing populist groups and parties deny anthropogenic climate change, question scientific findings and emphasise the economic disadvantages of climate and environmental protection measures. They also reject international cooperation on climate and environmental protection (Schaller and Carius 2019; Matlach and Janulewicz 2021).

During the 2021 federal elections in Germany, the AfD in particular emphasised its scepticism towards man-made climate change and climate protection measures. Climate change was a key issue in the election campaign, which increasingly shifted to the digital space. Right-wing extremist and right-wing populist groups, who see climate protection only as an instrument of ideological opponents, used social media to gain attention and support with emotional and polarising content. For example, research into the 2021 federal election campaign showed that opponents of climate protection measures often took information out of context. Exaggerated headlines from established media were used to lend greater credibility to misleading content. There was also a stylisation of the climate debate from the right into a "culture war", for example by frequently conjuring up hostile images ("climate hysterics", "climate terrorists", "the Greens"). And various disinformation narratives were used, such as the “denial and delay” narrative, which denied or glossed over climate change (Matlach and Janulewicz 2021; Federal Environment Agency (UBA) 2023).

Social media algorithms reinforce such right-wing populist campaigns by favoring posts with a high engagement rate, which often includes disinformation. This leads to a distorted perception of public opinions and makes it difficult to have an objective discussion, especially about climate protection (Klee and Midulla 2023).

Disinformation not only undermines the acceptance of scientific findings on climate change, but also delays urgently needed climate protection measures (Kaiser and Rhomberg 2016). To combat these destructive influences, it is crucial to provide reliable information and critically scrutinise political content for misinformation (CAAD 2023). Fact-checking organisations do important educational work by debunking manipulated evidence that denies or whitewashes anthropogenic climate change (Klee and Midulla 2023).

Successful climate and environmental policy relies on transparency, education and the dissemination of scientifically sound facts to effectively counter disinformation campaigns. Targeted education campaigns that provide factual information and motivate action are essential to raise awareness of environmental policy concerns and the need for environmentally friendly measures. The decisive fight against disinformation through evidence-based information dissemination and the support of fact-based journalism (possibly with special journalist briefings on topics, fact-checking, etc.) are very important to promote commitment to climate and environmental protection (Maurer et al. 2023). At the same time, the increasing importance of social media and digital technologies requires new approaches in political communication in order to effectively counter the challenges posed by disinformation and promote an informed public debate on environmental issues. It would also be conceivable to oblige companies that profit from the spread of disinformation and support this through corresponding algorithms not only to monitor their content more closely, but also to finance measures to train citizens to use social media critically. It would also be conceivable to oblige them to fund the development and implementation of strategies to identify and combat disinformation campaigns targeting environmental and climate issues.

2. Increase in anti-democratic tendencies within Germany

In Germany, the rise of populist parties, particularly the AfD, and other non-democratic movements is leading to stronger anti-democratic and anti-environmentalist tendencies. The AfD doubts anthropogenic climate change and criticises climate protection as an ideological project directed against “ordinary peo-

ple".[25] These positions, expressed as criticism of "climate hysteria", can delay or weaken the implementation of climate protection measures. The party rejects the energy transition and favours traditional energy sources, which runs counter to the long-term goals of the energy policy transition in Germany (Jacob et al. 2020). Despite differing views within the state associations, such as the pro-coal stance in Saxony and Brandenburg in contrast to the Bremen AfD, which is against coal-fired power plants, the AfD as a whole takes a unified stance against climate policies, which deepens the political divide in Germany (Götz and Kirchner 2016).

The increasing presence of the AfD in the federal states and at municipal level, including the assumption of district council and mayoral offices, makes it more difficult to design and implement uniform, progressive environmental policies nationwide. The previously defined, fixed responsibilities of the federal states and municipalities will in principle enable anti-democratic forces to undermine environmental, climate and nature conservation policy goals in various areas in the future and to initiate political measures that run counter to national or international environmental protection goals. This also increases the potential for direct conflicts between the federal and state governments.

The influence of right-wing populist parties extends far into political debates and decision-making processes at federal and state level, where their blocking of environmental policy initiatives undermines public trust in science and jeopardises sustainable development goals. Even where right-wing populists are not in government, they sometimes dominate the political discourse and restrict the scope of the other, democratic parties (Töller 2022).

Job cuts and the municipalisation of environmental protection tasks, i.e. the abolition of specialist authorities and the assignment of tasks to local authorities, have already weakened environmental protection and nature conservation. Reforms in individual federal states have led to the repoliticisation of environmental permits and the marginalisation of environmental initiatives (Schulze et al. 2008). These developments are already threatening the enforcement of environmental law. In order to prevent a further, significant weakening of environmental protection in Germany in the future as anti-democratic forces gain strength, it may soon be necessary, if current trends continue, to consider further (minimum) environmental policy requirements at federal level, to establish additional rules of cooperation at the lower levels of government and, in extreme cases, to reorganise the allocation of powers to the federal, state and local governments in the various environmental policy areas (Götz and Kirchner 2016). Furthermore, civil society involvement in the environmental sector in particular could be strengthened through programs to support NGOs and citizens' initiatives. These could act as a counterweight to right-wing populist and extremist political influences.

3. Increasing strengthening of autocracies worldwide

The global trend of increasing and growing power of autocratic regimes represents a significant hurdle for the political order and has far-reaching implications for international environmental and climate policy.

In autocratic systems, climate and environmental protection is often neglected in favour of political, economic and social goals, especially when economic performance appears to be affected by environmental regulations in the short term or when governments are dependent on energy exports (Melton and Marktanner 2021; Bauer 2023; Sinha et al. 2023). The generally higher importance of climate and environmental protection in democracies is reflected in a higher emissions burden in autocracies compared to democracies or in an increased emissions intensity per unit of income growth. An analysis of the environmental Kuznets curve for 150 countries from 1790 to 2010 shows that autocracies have higher CO_2 emissions than democracies as per capita income rises. Democracies implement more effective measures to reduce greenhouse gas emissions and set more ambitious national climate protection targets. Their efficiency in reducing CO_2 emissions underlines the importance of the political system for successful climate protection strategies (Sinha et al. 2023).

25 Interestingly, research shows that the AfD's policies are most likely to affect its own supporters (Fratzscher 2023). As people who see themselves as losers of modernisation are particularly susceptible to right-wing populists and far-right parties, narratives that certain policies are against the interests of ordinary people are helpful for parties such as the AfD (Gidron and Hall 2017). Social cushioning of economic and social restructuring is therefore important.

In addition to the low prioritisation of environmental aspects in authoritarian regimes, a lack of transparency and accountability in these countries leads to an increased risk of corruption (Hartmann 2022) which hinders climate and environmental protection initiatives as well as sustainable development. The generally much higher level of transparency and accountability in democratic states makes it easier to uncover and publicise negative environmental impacts and to monitor compliance with environmental protection laws more effectively (Fuhr and Taylor 2017; Transparency International Deutschland e.V. 2021). The increase in the number of autocracies is therefore directly relevant for European and international climate and environmental protection.

At European level, the rise of right-wing populist and autocratic tendencies poses a significant challenge to the European Union's common environmental policy. These political forces tend to place national interests above common European goals, which makes the implementation of EU-wide environmental legislation more difficult and can lead to a fragmentation of environmental policy within the EU. There is also a risk that the influence of these parties could block or weaken important environmental initiatives at EU level. One example of this is the delay in the implementation of the Green Deal, where some member states led by right-wing populist governments are resisting stricter environmental regulations. Right-wing populist parties in countries such as Poland and Hungary have also repeatedly blocked measures aimed at achieving the EU's climate targets. The results of the 2024 European elections, which resulted in a strengthening of right-wing populist forces in the European Parliament, suggest that political agreement on future environmental and climate protection measures is likely to be much more complex (Kielon 2024).

At the same time, a disunited EU has less influence on international negotiations and agreements, which can weaken the EU's global leadership role in environmental and climate protection. International environmental policy has become considerably more important in recent decades. There is now a complex system of autonomous international regimes, agreements and conventions. In addition, there is a highly differentiated institutional architecture with specialised and decentralised secretariats and a large number of intergovernmental committees and working groups, as well as various departments of the United Nations (UN) Secretariat, the UNEP environmental programme and the responsibilities and capacities of specialised agencies such as the United Nations Development Programme (UNDP), the Food and Agriculture Organization (FAO), the World Health Organization (WHO) etc. In no other policy field has there been such a large number of international conferences, meetings of states parties and follow-up process meetings as in the area of environmental policy since 1972 (Rechkemmer 2007).

These intensive political activities are the result of the fact that many environment-related problems can only be solved through international cooperation. If this cooperation is no longer guaranteed in the future, it will be difficult to respond adequately to essential environmental policy challenges.

There are currently no signs of a common, anti-environmental agenda among autocracies worldwide, nor are there any signs of an "autocratic international" in the immediate future. Autocracies base their foreign policy primarily on their immediate domestic interests and not on common overarching values. Cooperation tends to focus on individual issues and short-term questions. "In authoritarian-dominated organizations, member states are often reluctant to relinquish significant powers. The term 'collaboration' between authoritarian regimes reflects the mistrust visible here and avoids the normative connotation of cooperation." (Bank and Joshua 2017; p. 6).

Although a widespread attack on international environmental agreements is not to be expected in the medium term, the strengthening of authoritarian regimes will nevertheless lead to a foreseeable weakening of international environmental cooperation. Autocratic regimes are less likely to comply with international agreements and are less reliable when it comes to regional cooperation (Hartmann 2022). This is very problematic for maintaining or expanding international cooperation on environmental policy issues.

Conclusion for environmental policy and research

The worldwide decline in democratic stability reduces the ability of states to respond effectively to global environmental and climate challenges. The necessary transformations towards sustainability at a social and economic level, as well as other processes of change and crises, lead to concerns and fears among the population. Politicians must adequately address these concerns and fears, as otherwise there is a risk that autocratic tendencies will continue to grow. Populist parties and movements that critically question or block environmental protection measures are already gaining influence. The targeted dissemination of disinformation by authoritarian actors, particularly in relation to climate change, poses a serious threat that can undermine public support for climate and environmental protection measures.

Autocratic states, whose economic growth is heavily dependent on fossil fuels, often position themselves against increased international climate protection measures. In contrast, democracies tend to support climate and environmental protection through mostly more transparent institutions and accountability mechanisms at both national and international level. In order to advance global environmental and climate protection efforts, it is important to strengthen democratic principles and take action against authoritarian tendencies and disinformation. The promotion of citizen participation, civil society mobilisation, political initiatives to create a sustainable future together – all this helps to achieve a positive view of the current transformation process. German environmental policy can play an active role here in many areas.

The task of environmental policy can also be to make clearer the connections between autocracies and a backsliding on environmental protection issues. Just as German environmental policy must actively counter the disinformation of autocratic states, it should also be more active in pointing out where autocracies or governments moving in an autocratic direction are responsible for serious environmental or climate damage.

2.5 Military, war and the consequences of war

Trend: As a result of the Russian war of aggression in Ukraine, military conflicts have become very present in the perception of the European public. In addition to the devastating effects on the population and infrastructure, the environment and nature also suffer enormously from military conflicts – whether as a result of hostilities or targeted destruction. At the same time, there are also increasing efforts to achieve greater sustainability in the military sector. How can a forward-looking environmental policy meet these challenges and support this commitment?

Emerging Issues

- Environmental damage and consequences of war
- Environmental destruction as a war strategy
- Sustainable military

In a nutshell

- Armed conflicts and wars not only cause suffering and death, but also have a wide range of negative effects on the environment, some of which persist for decades after the end of the war. As a result of the Russian war of aggression against Ukraine, Europe is currently experiencing a paradigm shift in defence and security policy from a peace order to a conflict order as part of the "turn of an era". The number of armed conflicts and global military expenditure is rising and democratic societies are increasingly being challenged by hybrid warfare.
- Environmental aspects primarily concern three areas: firstly, the direct and immediate consequences of acts of war for the environment and people on the ground; secondly, the military itself and the technologies and resources it uses; and thirdly, the longer-term consequences and effects of the disposal of war material or reconstruction. In addition, there are starting points for closing regulatory gaps that affect all three areas.

Background

Global security has deteriorated significantly over the past ten years: In 2022, there were more wars worldwide than ever before, as well as significantly higher military spending (Stockholm International Peace Research Institute (SIPRI) 2023). There is therefore an increasing need to understand the environmental impact of wars and armed conflicts and to incorporate this into security policy considerations, conflict prevention strategies and peacebuilding.

Armed conflicts are inherently destructive. They not only lead directly to suffering and death, but also to environmental damage that has devastating effects on flora, fauna and people. The environmental impact usually far exceeds the duration of the conflict and continues to shape ecosystems decades after the end of the war. This includes the destruction of habitats through bombing and infrastructure damage, the release of pollutants and toxic substances from weapons and munitions that cause soil, water and air pollution, as well as massive deforestation and the loss of biodiversity through war activities. The relationship between conflicts and the environment is multifaceted. On the one hand, wars can lead to conflicts over natural resources such as water and land. On the other hand, the (over)use of natural resources can lead to conflicts. In addition, the effects of war on the environment (pollution, water shortages, etc.) can be a driver of environmentally induced migration. The long-term effects also include the many resources required for reconstruction after the end of the war.

Europe's new (in)security: from peace to conflict order

In the perception of many Western Europeans, war only returned to Europe with the Russian attack on Ukraine. However, the invasion by regular Russian troops on 24 February 2022 actually marked a further escalation in a series of conflicts following the end of the Cold War (Federal Agency for Civic Education (bpb) 2022b). After the end of the Second World War, there were numerous armed conflicts and wars in Europe in which hundreds of thousands lost their lives – including in Cyprus, Nagorno-Karabakh, the Balkans, Chechnya and Georgia (Editorial network Germany 2022). Nevertheless, the West has long relied on close trade relations with Russia, even in the recent past under Putin. The other wars that Russia waged after the collapse of the Soviet Union to secure its sphere of influence also had a regional rather than an international impact (Federal Agency for Civic Education (bpb) 2022b). Even the illegal occupation of Crimea in 2014 did not change Western attitudes. However, the recent Russian invasion of Ukraine has meant that the European security order, which had been established since the end of the Cold War to ensure lasting peace, stability and economic cooperation in the region, has been destroyed. Consequently, in February 2022, Federal Chancellor Olaf Scholz announced the so-called "turning point" for the Bundeswehr in a government declaration and heralded a paradigm shift in Germany's defence and security policy and a reshaping of the European security order. The core of this is to ensure lasting security and democracy in Europe, not only to name Russia's war of aggression as a violation of international law and to sanction the country, but also to actively support Ukraine (Press and Information Office of the Federal Government 2022).

The liberal world order that has emerged since the fall of communism and the opening of the so-called Iron Curtain in 1989/90 is seen as a key political and economic driver of progress, peace and prosperity, particularly in democratic countries. However, we are currently witnessing how this unipolar world order under the supremacy of the USA is being challenged by geopolitical rivals such as China, Russia and Turkey. The post-Cold War international order is currently changing into a new bi- or multi-polar world order, and it is currently unclear how much will remain of rules-based multilateralism. In particular, Russia's attack on Ukraine and the military escalation of the Middle East conflict in 2023 could be seen as crystallisation points for the turning point in international relations in the future (Friedrich-Ebert-Stiftung 2023a).

Germany is involved in a large number of international organisations that serve different purposes. In addition to the EU, the best known and most important are the United Nations and the North Atlantic Treaty Organization (NATO) (Federal Agency for Civic Education (bpb) n.d.). With the renewed East-West confrontation since the Russian attack on Ukraine, the importance of NATO as a defensive alliance in particular has come back into political focus and has led to a reorientation of security policy in many European countries. Finland and Sweden, for example, have given up their military neutrality and joined NATO (Federal Agency for Civic Education (bpb) n.d.).

When do we speak of war?

The Arbeitsgemeinschaft für Kriegsursachenforschung (AKUF) defines **war** as a violent mass conflict that has all of the following characteristics:

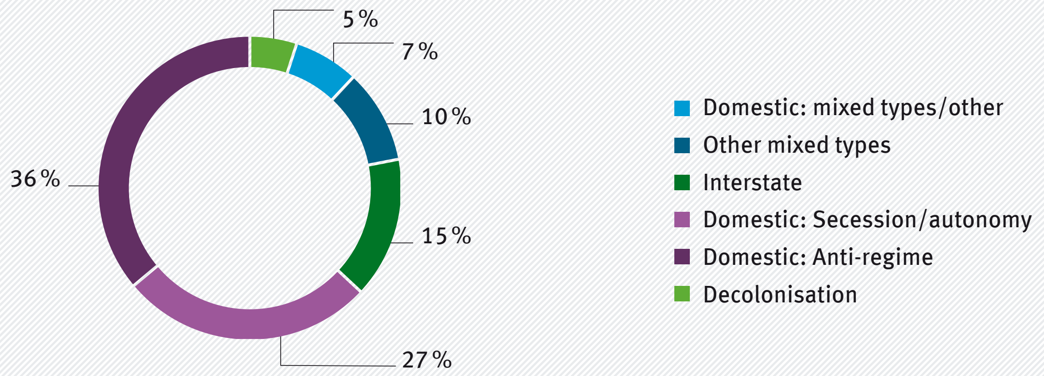
- two or more armed forces are involved in the fighting, at least one of which is a regular armed force (military, paramilitary units, police units) of the government;

- on both sides there must be a minimum of centrally directed organisation of the belligerents and of the struggle, even if this means no more than organised armed defence or planned raids (guerrilla operations, guerrilla warfare, etc.);

- the armed operations take place with a certain continuity and not just as occasional, spontaneous clashes, i.e. both sides operate according to a planned strategy – regardless of whether the fighting takes place on the territory of one or more societies and how long it lasts (University of Hamburg 2016).

Figure 09

Types of war since 1945



Source: own representation according to Schreiber 2021

Violent conflicts in which not all criteria are fully met are referred to as **armed conflicts** (University of Hamburg 2016).[26] Furthermore, the AKUF distinguishes between the following five types of war: anti-regime wars, wars of autonomy and secession, interstate wars, decolonisation wars and other wars. Many wars cannot be clearly categorised because different types overlap or the character of the war changes over the course of the conflict, resulting in mixed types (University of Hamburg 2016). The two most common types of war since 1945 are domestic anti-regime wars with 36% and domestic autonomy wars with 27% (see Figure 9).

Global conflict and war landscape and military spending

In 2022, there were numerous armed conflicts around the world, with the number and extent of violence varying greatly from region to region. In 2022, the war in Ukraine was the only major interstate war in which standing armies were involved. Outside Europe, most wars took place within states or in confederations with porous borders (Stockholm International Peace Research Institute (SIPRI) 2023). A total of 56 states were affected by armed conflicts in 2022 (see Figure 10). This is five states more than in the previous year (Stockholm International Peace Research Institute (SIPRI) 2023). A further 16 cases involved intense armed conflicts.

In the course of numerous armed conflicts, many countries have rearmed. Rearmament is the increase in the military potential of an individual state or a military alliance. This can be achieved both by modernising armaments and by increasing the size of the armed forces, and can serve both to prevent war through deterrence and to prepare for military action (Friedrich-Ebert-Stiftung 2023b).

Global military expenditure reached a new record in 2022 (Statista GmbH 2023b). In 2022, global spending amounted to around 2.24 trillion US dollars (see Figure 11). The USA had the largest national military expenditure in this period with USD 877 billion, followed by China with USD 292 billion and Russia with USD 86 billion (Statista GmbH 2023b). In response to the Russian attack on Ukraine, European countries in particular have increased their military spending. The German defence budget will grow by 1.7 billion to 51.8 billion euros in 2024 and is intended to ensure that Germany makes its two per cent contribution of gross domestic product to NATO capability goals from 2024 (Federal Ministry of Defence (BMVG) 2023).

26 Wars are considered to have ended when hostilities have ceased permanently, i.e. for a period of at least one year, or have only continued below the above-mentioned criteria (University of Hamburg 2016).

Destabilisation of democratic societies by means of hybrid warfare

The way in which wars are waged has changed repeatedly over time and adapted to the respective conditions, available technologies and balance of power. The term "hybrid warfare", which has been used since around 2005, refers to the combination of military and non-military means of conflict that are used openly or covertly (Scheffran 2019). The targeted combination of political, economic, media, intelligence, cyber-technical (see chapter 2.9) and military forms of combat is intended to create or reinforce political, economic and social instability in the target states (Federal Agency for Civic Education (bpb) 2022a). Legal and moral grey areas between war and peace emerge, which lead to complex conflict dynamics, encompass all areas of society and reinforce underlying problems (Scheffran 2019). A central motive of the warring parties is to make it impossible to attribute (international) legally and morally impermissible acts and to weaken the opponent without formally declaring war (Federal Agency for Civic Education (bpb) 2022a).

A look into the future

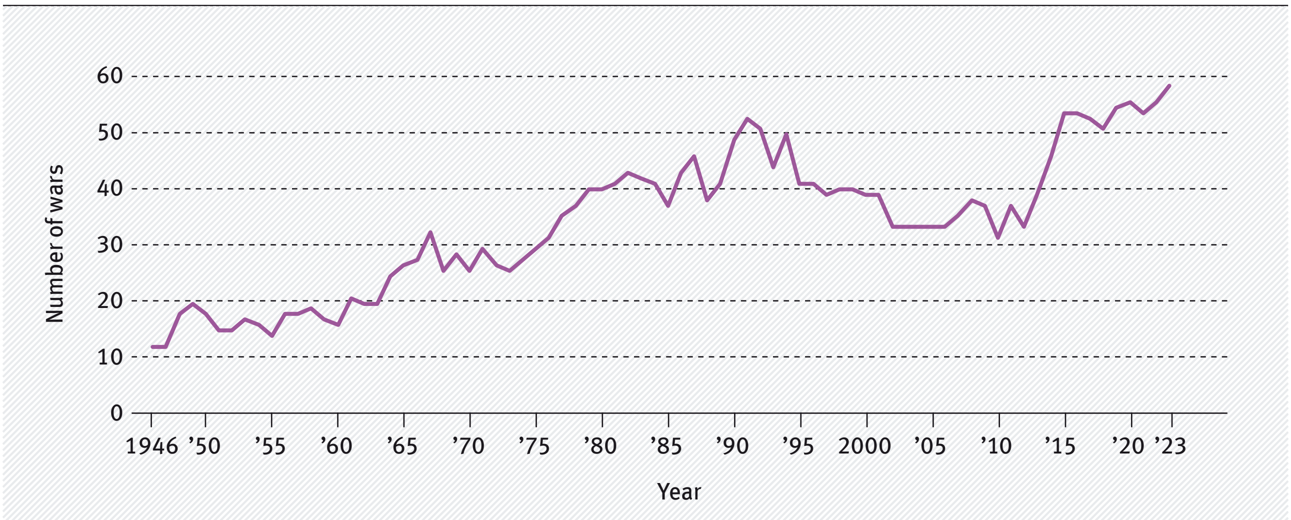
The outcome of armed conflicts is difficult to predict. In order to be prepared for possible outcomes, scenario techniques have been established in warfare, for example. As part of strategic foresight, scenarios are used today in a variety of fields of action in order to take account of the fact that the future is unpredictable and that complex, dynamic interactions can lead to a variety of alternative possible futures.

For example, the European Parliament conducted a foresight study on future relations between the EU and Ukraine and developed four scenarios for 2035, which are summarised in the following box (Damen 2023). Even if the scenarios have a deterrent effect in some cases, they can serve as elements for strategic considerations by various political players and also provide indications of possible environmental impacts, irrespective of geopolitical consequences.

- **Scenario 1** Fair stability: Ukraine regains all of its territory and joins the EU and NATO, while a new cooperative Russian regime signs a peace agreement.
- **Scenario 2** Cold War II: Neither of the two warring parties gains the upper hand. A new bipolar world emerges. Ukraine is partially integrated into the EU and NATO.
- **Scenario 3** Frozen conflict: The front comes to a standstill and the warring parties negotiate compromises, leading to Ukrainian neutrality and a stagnating EU accession process.
- **Scenario 4** Destroyed Europe: Russia escalates the war, leading to NATO involvement. This re-

Figure 10

Total number of civil wars and interstate conflicts worldwide from 1946 to 2020



Source: own representation according to Statista GmbH 2023b; p. 13

sults in a strengthened and expanded NATO, but a disunited, weak EU.

With regard to the impact on environmental policy, the Emerging Issues section addresses the following questions:

1. What are the consequences of war for the environment?
2. How is environmental destruction specifically used as a war strategy?
3. How can the military be made more sustainable?

Emerging Issues

For thousands of years, mankind has been waging wars that have caused considerable environmental damage as well as human suffering. This is particularly due to the fact that the environment is neglected in times of war and its importance is subordinated to military priorities (Oberschmidleitner 2013). Armed conflicts are increasing worldwide (see background) and further conflicts may arise. It is therefore all the more important to be aware of the environmental impact. What are the ecological consequences of wars, what role does targeted environmental destruction play and would a sustainable military be conceivable?

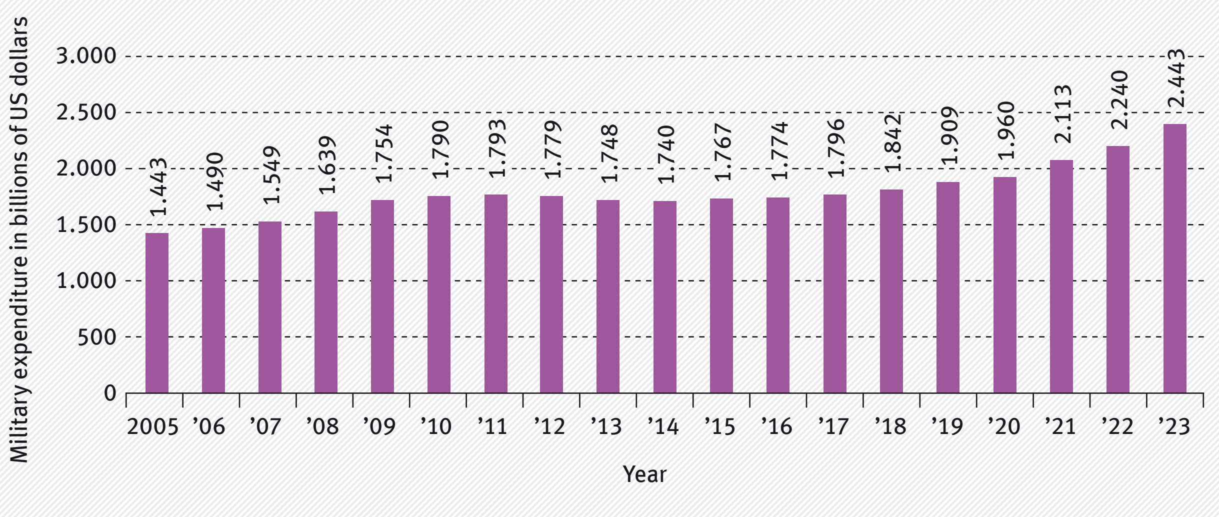
1. Environmental damage and consequences of war

The environment forms the battlefield, the physical place where wars are fought, and is thus inevitably affected by warlike activities (Repez and Atanasiu 2019). Many resources are also needed for reconstruction, for example, to build homes that have been destroyed by missile strikes. The environmental damage caused by wars is seen as an unavoidable side effect, i.e. as collateral damage that often receives little attention (Lohbeck 2004). Instead of worrying about environmental impacts, the top priority of the warring parties is to achieve their war aims as effectively as possible. The war claims full social and political attention, while the environment takes a secondary place (Schiefer 2022). However, given the urgency of the climate and biodiversity crisis, it is important to pay greater attention to the environmental consequences of wars and not to lose sight of the relevance of climate and environmental protection even in conflict situations. This is because the effects of wars often last far beyond the duration of the conflict and have an impact beyond the borders of national territories, for example when a large number of new homes have to be built following missile strikes (Reuß and Schäfer 2012).

Newer practices of modern warfare also entail unprecedented burdens. Although military applications are often drivers of innovation, their production and operation often involve a very high consumption of

Figure 11

Global military expenditure from 2005 to 2022 (in billion US dollars)



Source: own representation according to Statista GmbH 2023b; p. 56

energy and resources. The use of artificial intelligence in the military, for example, is increasing in the Russian-Ukrainian war, as it is used to model battlefields and identify enemy objects (Kreye et al. n.d.). Research projects are exploring the integration of AI into military affairs, including unmanned watercraft (U.S. Department of Defense 2023) intelligent drones and autonomous weapon systems (Riedel 2022). High-energy laser weapons could also be increasingly used. For example, the German Armed Forces shot a drone out of the sky with a laser weapon for the first time in 2022 (Aviation Media & IT GmbH 2022) and Russia claims to have already used laser weapons in the Russian-Ukrainian war (Ghaedi 2022). Both high-energy lasers – for generating the laser beam (Bohnenstengel 2021) – as well as AI have a high energy consumption (Muller and King 2023). Training a complex neural network for an NLP AI model[27] emits five times more CO_2 than a car in its entire life cycle, according to a study by the University of Massachusetts Amherst (Strubell et al. 2019). There is also a risk that a more efficient design of AI-controlled drones, for example, could lead to increased production and use, which in turn could increase greenhouse gas emissions (Just and Damm 2021). Depending on how hybrid warfare develops in the future, the environmental impact of warfare could therefore continue to increase.

Environmental impacts as a result of wars are considered in terms of two different temporal stages: short-term, i.e. during the acts of war, and indirect, i.e. at a later point in time as a consequence of the acts of war.

Even acute warfare has a considerable impact. Military vehicles such as tanks or fighter jets cause large quantities of CO_2 emissions, damage soils and infrastructure due to their weight and disturb flora and fauna with noise (Scheffran 2020). High-frequency signals from ships or submarines can damage the inner ear of dolphins and whales, for example (Tsiptsiura 2022). In addition to these environmental impacts caused by acute physical warfare, the use of modern military technologies also has consequences.

As a direct consequence, wars leave destruction in their wake – to buildings, infrastructure and nature – and war waste that has long-lasting effects on the environment. Pollutants from bombs or munitions containing uranium, for example, contaminate the soil and end up in the groundwater (Auernheimer 2022). In addition, the destruction of buildings and infrastructure releases any pollutants they may contain – for example, many houses destroyed during the war in Ukraine are contaminated with asbestos (Nielsen and Hodgkin 2022). It is not only difficult to dispose of war material, but also other waste during warfare. In addition, bomb or missile strikes lead to fires and emit greenhouse gases (Tsiptsiura 2022). There are also large movements of refugees fleeing war, which consume fuel and pollute the surrounding ecosystems by creating refugee camps (Scheffran 2020). Wars cause poverty and force people to use natural resources recklessly, for example for firewood, and can thus turn the surroundings of refugee camps into wasteland (Welzer 2010). In addition, the economic pressure caused by cost-intensive warfare can encourage conflict parties to extract existing resources in an unsustainable, purely profit-driven manner, which further pollutes the environment in conflict areas and also enables third parties to profit economically from the war (Le Billon 2001).

Even after wars, the environment remains burdened as an indirect consequence. On the one hand, this results from the fact that after the war, states focus their attention on solving social problems resulting from war, such as poverty and securing the basic needs of the population, which means that only limited resources are available for a sustainable climate and environmental policy (Schiefer 2022). On the other hand, further burdens arise from the necessary reconstruction, as wars destroy homes, roads, bridges, railroad stations, airports and more, with cement production being particularly emission-intensive (Martin Auer 2020). In Ukraine, around 150 million tons of CO_2 were emitted by the war in the first 18 months of the war until September 2023 – this is roughly equivalent to the annual emissions of a country like Belgium. At 36%, the reconstruction of buildings and infrastructure is the largest cause of emissions (Klerk et al. 2023).

At the same time, there is an opportunity for green, sustainable reconstruction, including through increased investment in modern technologies. Concepts for a sustainable reconstruction program are already

27 Natural language processing refers to the type of AI application to which ChatGPT, for example, belongs.

being developed for Ukraine, for example by the Federal Environment Agency (Hermann and Rosenbaum 2022) or the Low Carbon Ukraine initiative funded by the BMUV (Saha et al. 2022). In 2024, the UN Environment Programme (UNEP), the UN Economic Commission for Europe (UNECE) and the Organization for Economic Cooperation and Development (OECD) presented the "Platform for Action on the Green Recovery of Ukraine" in Berlin as part of the Ukraine Recovery Conference, which aims to coordinate international efforts for environmentally friendly, sustainable reconstruction (United Nations Environment Programme (UNEP) 2024). In view of the aforementioned hurdles to sustainable action in times of war, it is all the more important to emphasise that Ukraine has continued to actively pursue environmental issues since the beginning of the war and that the Environmental Impact Assessment Act 2023, for example, has been slightly adapted, but[28] has been fundamentally retained (Pragma Consulting Group 2023).

2. Environmental destruction as a war strategy
While the main objective of war is to defeat the enemy, environmental destruction as a war strategy aims to weaken the enemy by attacking its ecological support systems. War strategies include, for example, the use of environmentally disruptive technologies or the targeted destruction of critical infrastructure. The aim is to use the environmental forces thus released as a weapon to harm the enemy and leave behind so-called scorched earth (Lohbeck 2004). The manipulation of the environment for military purposes dates back to antiquity, for example by poisoning bodies of water (Reuß and Schäfer 2012). Nowadays, various agreements prohibit targeted environmental damage in times of war. However, prosecution is difficult due to very high legal hurdles and other factors. For example, even in a catastrophic situation such as a nuclear meltdown, it is impossible to predict what kind of environmental damage the International Criminal Court would consider sufficiently devastating; in addition, it is unclear, for example, how an arrest

28 Under the amended law, direct repairs to destruction caused by acts of war do not have to undergo an environmental impact assessment (Pragma Consulting Group 2023).

warrant against Russian commanders would even be enforceable (Wilson 2023). Nevertheless, targeted environmental destruction is still used today for strategic reasons, as can be seen in the war in Ukraine. The fact that war is being waged in Ukraine for the first time in a long time in a heavily industrialised country poses considerable dangers for societies in Europe and beyond (Hohmann and Hugo 2023). Modern warfare and advanced weapons technologies have a particularly destructive power, and there are more points of attack for targeted destruction of facilities with devastating effects on the environment, such as gas pipelines and nuclear power plants, which did not exist in the past.

The use of environmentally destructive technologies, such as biological and chemical weapons, can have serious environmental consequences. A telling example is the Vietnam War, which was the first modern conflict which saw targeted environmental destruction used as a war tactic (Oberschmidleitner 2013). The USA sprayed around 45 million litres of the herbicide Agent Orange to defoliate the rainforest, deprive Vietnamese soldiers of cover and improve visibility in the field (Repez and Atanasiu 2019). Other herbicides such as Agent Blue were also used to destroy agricultural land (Rüffer 2022). These herbicides contaminated soils and water bodies, with long-term effects on nature and the population (Scheffran 2020). After the devastating environmental consequences of the Vietnam War, the use of environmentally damaging techniques was banned in 1977 by the ENMOD Convention (Reuß and Schäfer 2012). In addition, the Biological Weapons Convention has been in force since 1975 and the Chemical Weapons Convention since 1997 (Federal Agency for Civic Education (bpb) 2015).

Conflict parties also try to create environmental impacts by attacking critical infrastructure. There are many examples of this. In the second Gulf War, for example, Iraqi troops set fire to oil wells in Kuwait in order to destroy resources. This led to the pollution of air, soil and water, and even non-warring parties such as Turkey, Iran and Oman had to contend with “black rain” afterwards because soot sank down with rain as a result of the fire. At the time, CO_2 emissions accounted for 2 to 3% of global emissions from fossil fuels (Auernheimer 2022). Even today, Ukraine’s critical infrastructure is under repeated Russian attack, particularly power plants, oil refineries and heavy industry sites. These attacks can release highly toxic substances into the soil, groundwater and air (Hohmann and Hugo 2023). The bombing of the Kachovka dam, for example, is said to have resulted in around 150 tons of engine oil entering the Dnipro River (Zeit Online 2023). The weapons and ammunition that were washed away can pollute the soil and water due to the heavy metals and high-energy materials they contain. The water level of the Kakhovka reservoir is also important for the cooling water of the reactors of the Zaporizhzhya nuclear power plant. If the level of water falls below a critical level, the situation is unsafe and potentially dangerous (tagesschau.de 2023a) as radioactive radiation would be released in the event of a core meltdown.

The targeted attack on the Nord Stream 1 and 2 gas pipelines as part of the Russian-Ukrainian war also resulted in enormous environmental damage. With emissions of around 14.6 million tons of CO_2 equivalents by October 2022, this sabotage represented the largest single cause of emissions from the war in Ukraine (Michaelowa 2023).

In addition to conventional warfare, cyber warfare is increasingly being used to attack critical infrastructure and damage the environment. The power supply in Ukraine (Kolvenbach 2022) and nuclear power plants have already been the subject of cyberattacks. In 2010, for example, the control software of a nuclear power plant in Iran was hacked in order to control the rotation frequency of uranium centrifuges, i.e. to influence industrial control systems (Muth 2020). Such attacks on the energy supply could lead to a power outage, which would have fatal consequences for the environment surrounding nuclear power plants, for example. In addition to the negative environmental consequences of a successful cyberattack, cyber warfare has other negative effects. It is not only the cyberattack itself that consumes energy. The infrastructure used by states and companies to defend against cyberattacks – data centres, hardware, software –consumes considerable amounts of energy (Schmid 2022).

3. Sustainable military

The military and defence industry causes around 5.5% of greenhouse gas emissions worldwide and consumes a high amount of resources. If the world’s armed forces were a country in their own right, they would have the fourth largest CO_2 footprint globally, larger than that of Russia (Parkinson and Cottrell

2022). Climate change is becoming ever more present, and yet armaments are being deployed worldwide. If the NATO member states were to achieve and maintain the alliance targets for the years 2024 to 2028 of spending 2% of GDP on military expenditure and investing 20% of this in new equipment, the CO_2 footprint of NATO forces would increase by 50% compared to 2021 – to 196 million tons of CO_2 equivalents (Lin et al. 2023) which would significantly exceed the total greenhouse gas emissions of the Netherlands for 2023 (150.75 t; European Commission 2024).

The German Ministry of Defence is focusing on an efficient Bundeswehr, and special funds were made available for this in 2022 (Federal Government 2022). However, while the defence sector has hardly played any role in climate policy in the past, with militaries explicitly excluded from the emissions targets and the emissions reporting obligation in the 1997 Kyoto Protocol (Peil 2021), the Russian-Ukrainian War, among other things, has highlighted the importance of the sector in climate policy (Michaelowa 2023). It is becoming increasingly clear that negative dependencies must be overcome in order to ensure strategic autonomy, to which environmental friendliness can contribute (Bosch and Vinke 2022). Increased integration of renewable energies into the military, for example, can also ensure independence from energy supplies in a military context, especially as the availability of fossil fuels will continue to decline. “Green” military strategies and a “sustainable” military are therefore becoming increasingly important. NATO, for example, adopted an action plan in 2021 to link security policy and the climate crisis (North Atlantic Treaty Organization (NATO) 2021). However, there is no binding set of rules as of yet (Michaelowa 2023).

According to the Federal Ministry of Defence’s sustainability report, the German armed forces emitted a total of 1.71 million tons of CO_2 in 2021, excluding foreign deployments (Federal Ministry of Defence (BMVG) 2022), comparable with the CO_2 emissions balance of Malta (Urmersbach 2023). Of the emissions, 54% are attributable to real estate and 46% to mobility (Federal Ministry of Defence (BMVG) 2022). The main causes of emissions are the fuel consumption of tanks, aircraft and ships. For example, a Eurofighter generates 11 tons of CO_2 in just one hour of flight (Auernheimer 2022), equivalent to the annual CO_2 emissions of an average German citizen (Statista GmbH 2024b). On the other hand, electricity and heat consumption in military properties are the main drivers of emissions.

Efforts to achieve a sustainable military are aimed at reducing emissions from domestic and operational properties through innovative technologies. These include the increased use of renewable energies such as solar thermal energy, photovoltaics and wind power, the defossilisation of the energy supply in Switzerland, the replacement of fossil heating systems with heat pumps, for example, and the renovation and energy-efficient construction of military buildings. In operational bases, which are mostly located in warmer regions, efforts are being made to reduce the consumption of fossil fuels required for air conditioning systems by using solar thermal cooling systems (Federal Ministry of Defencce (BMVG) 2022). This could enable the properties to achieve net climate neutrality in the future.

Reducing fossil greenhouse gas emissions in military mobility is proving more difficult. Ideas for the use of synthetic fuels produced from sustainable electricity, water or CO_2 from the air exist (Federal Ministry of Defence (BMVG) 2022). However, military vehicles require powerful drives and energy sources with a high energy density (Federal Ministry of Defence (BMVG) 2022), for which no environmentally friendly solutions are yet available on an industrial scale (Scientific Services of the German Bundestag 2020). A direct transfer of civilian energy and mobility concepts to the military is not possible (Federal Ministry of Defence (BMVG) 2022). A mix of synthetic and fossil fuels is therefore planned for the time being (Weinzierl et al. 2021). Nevertheless, research is being conducted into synthetic fuels (Federal Ministry of Defence (BMVG) 2022), so that in the future a Eurofighter could fly on CO_2-neutral synthetic kerosene alone. One advantage of this would be that vehicles would not have to be replaced or extensively retrofitted, as the fuels would be used in conventional engines (Weinzierl et al. 2021). Hydrogen and hydrogen fuel cells also play an important role in the military's focus on sustainability (Struck 2023). The German Bundeswehr's Class 212A submarine already uses hydrogen fuel cells in combination with diesel generators (Bundeswehr n.d.). Unmanned aerial vehicles also show potential for fuel cell applications (Struck 2023). However, pure hydrogen has a low energy density, which would lead to large tank volumes in relation to the available space in heavy vehicles (Struck 2023). It would therefore make sense to switch to synthetic fuels for heavier vehicles and to use hydrogen drives for lighter vehicles (Struck 2023). Even though the share of renewable energies in total gross electricity demand was 52% in the first half of 2023, synthetic fuels (Rudolph 2019) and the production of hydrogen still require considerable amounts of renewable energy due to electrolysis (Federal Government 2023b).

Electric drives would also minimise the consumption of fossil fuels and exhaust emissions. The German company FFG (Flensburger Fahrzeugbau GmbH) has developed the hybrid tank "Genesis", which offers a range of 150 km at 40 km/h in all-electric mode and a range of 600 km at 60 km/h in diesel-electric mode (FFG Flensburger Fahrzeugbau GmbH). For military purposes, the use of fully battery-powered tanks or electric jets would still require numerous innovations, as range is crucial. Charging infrastructure issues would also become increasingly important in war zones. For the time being, only hybrid vehicles are foreseeable (Struck 2023). It is important to note that the batteries required for electric and hybrid drives consume finite resources such as lithium (Mrozik et al. 2021). As large batteries are required for heavy electric vehicles such as tanks, sustainable dismantling and recycling are crucial for a positive balance in electromobility (European Commission (EC) 2020b).

Conclusion for environmental policy and research

In addition to the devastating effects on the people affected, wars and military operations also result in serious environmental damage both during and after conflict. And regardless of whether the number of wars and conflicts increases in the future, it can be assumed that the military will become even more technologised and will require more resources.

At present, it is not yet possible to predict with certainty how the global conflict structure will develop and what specific environmental impacts the new hybrid warfare in particular will have. Nevertheless, it is clear that the environment is damaged as a "silent victim" in armed conflicts and that its protection is of fundamental importance.

Environmental policy can promote environmental protection before, during and after armed conflicts, using various approaches. One way of intensifying environmental protection during armed conflicts and in their aftermath could be a binding, effective set of rules developed in peacetime to protect the natural environment in the course of military action. Here it is also important to close regulatory gaps and exchange experiences and best practices, for example on dealing with war waste and regulations for reconstruction, taking into account resource concerns and consequences for flora and fauna. In the event of war, stricter sanctions for violations and consistent punishment could also be a measure. Further supporting measures would be the introduction and implementation of ambitious environmental standards in the procurement of military equipment and the operation of properties, as well as the assessment of environmental impacts, particularly in connection with military exercises. Up to now, for example, it has been the responsibility of the Federal Ministry of Defence to decide on the application of the Environmental Impact Assessment Act for projects that only serve the purpose of defence.

Investments in research projects for the development of innovative technologies in the military sector also play an important role in promoting emissions reduction and a sustainable transformation of the military itself. In addition, studies that examine and highlight the environmental impact of armed conflicts, for example, could be promoted and made accessible to the public in order to raise awareness among current and future generations of the environmental risks of armed conflicts. This will also contribute to the development of long-term strategies for warfare that are, as far as possible, less damaging to the environment, people and infrastructure. Supporting non-governmental organisations (NGOs) and civil society organisations that are committed to environmental protection in conflict areas can be another supportive measure to minimise the environmental impact of wars.

In war situations, political attention shifts to security policy –- at the expense of environmental policy. This is also reflected in the distribution of budget funds: in 2023, for example, NATO member states spent USD 1.26 trillion on their armed forces – a sum that could have paid for twelve years of climate financing for poorer countries; and if all NATO member states were to reach their spending target of 2% of GDP for the next five years, the resulting 2.57 trillion US dollars would be sufficient to cover the climate adaptation costs of all low- and middle-income countries for the next seven years (Lin et al. 2023). Even at national level, spending on security and the military inevitably competes with urgently needed investments in climate and environmental protection in a limited federal budget. Against this backdrop, climate and environmental policy must be designed to be resilient to external influences and crises. This is the only way to ensure that environmental issues, which also directly affect the living environment of many people, are not pushed off the agenda during armed conflicts and that the implementation of a sustainable transformation is not slowed down overall.

2.6 The crisis society

Trend: “crisis mode” was named term of the year in 2023 by the German Language Society (GfdS). There have always been crises, but they seem to be increasing particularly strongly at the moment. The Covid-19 pandemic is still having an impact, war is raging in Ukraine and the climate crisis is becoming more urgent every year. At the same time, new threatening developments are emerging – war in the Middle East, inflation, a sluggish economy and a shift to the right. The state of emergency has become normality. So what constitutes a crisis society? What are the reasons for ongoing permanent stress? What coping strategies has the German population developed and how should the German government respond?

Emerging Issues

- Escape from reality: crisis resignation and crisis denial
- Demand to combat the crisis: increase and intensification of protests
- Caught up in the mood of crisis: the stressed working society

In a nutshell

- Germany is currently in a phase of polycrisis, in which various crises are occurring in parallel. Over the past ten years, an increasing prevalence of stress, exhaustion and stress-related illnesses can be observed. Many people feel insecure, worried, angry or helpless. However, crises do not affect everyone in the same way. Stress levels vary depending on personality and life situation. In addition, certain population groups are more challenged by crises and structural conditions than others, who in turn perceive objectively less demanding circumstances as more threatening. A look into the future suggests that ecological factors will be an increasing source of new stressors in the medium and long term. The changing environmental situation could therefore mean additional stress for people in Germany.
- The polycrisis, and the response to it, is placing an increasing burden on our society and jeopardising the transformation to sustainability. The reactions to the polycrisis – flight from reality, increasing protest activities and rising stress in the world of work – underline the need for a comprehensive and adaptable environmental policy. Environmental policy must address this by transforming fears into confidence and building trust on the one hand, and by creating opportunities for particularly committed citizens to exert influence and interact with protest movements on the other. At the same time, it is important to promote resilient working models that increase productivity and well-being at the same time.

Background

The term crisis describes a critical or decisive phase in a process or situation that is associated with uncertainty, danger or difficulties. It can affect various areas of life or society, including personal, economic, political or social aspects. Crises are the culmination or turning point of ongoing disruptions that no longer allow "business as usual". They call for the questioning of established routines so that the valley of persistent disruptions and problems can be overcome and a phase of positive development can follow (Steg 2020; Schubert and Klein 2021).

Crises can have different backgrounds and causes. They can be triggered very suddenly by events such as the death of a loved one or natural disasters. They can also develop slowly and build up over years, for example due to an unhealthy lifestyle, neglect of relationships, bad investments or overexploitation of the environment. Crises are generally unpleasant and not a desirable state. At the same time, research indicates that confronting crises is an important part of personal and social growth if they are overcome. The experience of being able to master challenging situations strengthens self-confidence and the ability to cope better with disruptions in the future (Bengel and Lysenko 2012; Krol 2024).

Crises also offer the opportunity for a reorientation that has a positive effect in the medium and long term. Entrenched structures and patterns of action can be resolved and sustainable ones established. For example, reforms implemented as a consequence of the 2008/2009 financial crisis have stabilised the international financial system in the long term (Federal Ministry of Finance (BMF) 2019). The truism "in every crisis there is also an opportunity" is therefore entirely justified. However, it is important that the intensity of the crisis does not leave those affected permanently overburdened, hopeless and with a deep sense of powerlessness.

Germany is currently facing multiple crises in parallel. There is talk of an ongoing period of polycrisis (Homer-Dixon et al. 2022). This refers not only to the consequences of the Covid-19 crisis since the beginning of 2020, but also the effects of the Russian war of aggression on Ukraine since February 2022, the Middle East conflict, which reached a new level of escalation at the beginning of October 2023, and, in addition, the longer-lasting and more far-reaching ecological crises such as climate change, biodiversity loss, environmental pollution[29] and increasing water scarcity (see chapter 2.2).

The multiple crises are accompanied by consequences that can themselves be perceived as crises, such as the development of energy prices, inflation or migration to Europe or Germany, as well as the increasing support for right-wing populism or the loss of trust in democratic institutions (see chapter 2.4). In addition, the temporal overlapping of numerous crises and their unclear duration lead to a form of crisis permanence, in which crises can be perceived as a permanent or almost normal state. This can lead to persistent stress and mental health problems.

Germany – permanently psychologically burdened

Over the past ten years, an increasing prevalence of stress, exhaustion and stress-related illnesses can be observed in Germany. For example, 26% of respondents to a representative survey in 2021 stated that they frequently experience stress. This is an increase of 6 percentage points compared to 2013 (Voermans et al. 2021; p. 8 f.). A representative study from 2023 even came to the conclusion that around 45% of 14 to 49-year-olds in Germany suffer from stress and around 36% from exhaustion (Schnetzer 2023).

Stress describes a strong strain on an organism caused by internal and external stimuli (so-called stressors). The processing of these stimuli must generate an adaptive reaction in the organism. The body is put on alert and reacts by releasing hormones such as adrenaline and cortisol, which provide additional energy and performance in the short term. For long-term health, however, it is important that phases of stress-related tension are followed by regular phases of relaxation and recovery (ERGO n.d.; Voermans et al. 2021; p 5 ff.). Otherwise, prolonged stress can lead to mental illnesses such as depression or burnout and also put a strain on mental health. Long-term stress reduces the ability to concentrate and increases the risk of heart attack and diabetes (GEO Knowledge 2022).

29 Also known as the "triple crisis".

Mental illness is now one of the third most common reasons for sick leave at work (Hildebrandt et al. 2023; p. 18). The number of reported days off work (AU days)[30] has risen significantly since 1991. The value was 301 per 100 insured years in 2022 and 323 per 100 insured years in 2023 (2023) (Federal Statistical Office (Destatis) 2023a; Dehl et al. 2024).

Not everyone is the same as before the crisis

People can deal with mental stress and the associated stressors to varying degrees. Dealing well with crisis-related stress means that the body is activated to an appropriate degree. The body does not react to existing stressors any longer or more intensively than is absolutely necessary. People with stable psychological resistance (resilience) react more moderately to stress and are able to regulate physical tension. The release of stress hormones is reduced and the metabolism is brought back to a healthy normal level. Why some people have more psychological resilience than others has been the subject of science and research since the 1950s (Bengel and Lysenko 2012; Krol 2024).

It is scientifically proven that the following factors promote mental resilience:

- a stable social environment and at least one permanent caregiver in childhood and adolescence;
- at least average intelligence, the ability to think outside the box, good access to emotions and
- a realistic self-image, self-efficacy experience, seeing a meaning in life, confidence (Krol 2024).

There is also a consensus that psychological resilience can fluctuate depending on the phase of life. For example, the period between leaving school and the age of thirty is generally characterised by personal insecurity and weaker resilience. The same applies to the first few years after leaving work. There is often a lack of stability and orientation during such phases of upheaval. A lack of stability and uncertainties demand personal energy resources, which means that confronting additional challenges can quickly lead to overload (Frick et al. 2022; Krol 2024). This is confirmed by experience from the Covid-19 crisis. For example, an analysis of the social consequences of the

30 Days of incapacity for work (AU days) are calculated per 100 insured years in order to obtain a standardised and easily understandable figure for the sickness rate. To obtain the value for an individual insured person, the total number is divided by 100.

pandemic shows that children and young people in particular have suffered from the consequences of the pandemic and are struggling with physical and mental illnesses, including depression and obesity (Federal Government 2023d).

In addition to individual, (social) psychological conditions, there are also systemic conditions that significantly affect people's resilience to crises: On the one hand, depending on the crisis, certain groups of people are under more physical and psychological strain than others – due to the system. During the Covid-19 pandemic, for example, this particularly affected doctors and nursing staff. They had to take on extra shifts and work under enormous time and performance pressure to prevent the healthcare system from collapsing. Their work was essential to the system. Families, especially single parents, were also under great strain. They were unable to send their children to daycare or school and had to manage paid work, childcare and homeschooling at the same time. On the other hand, people have different resources and framework conditions at their disposal to cushion the impact of stress and allow phases of tension to be followed by regular phases of relaxation. For example, the war in Ukraine was accompanied by a very sudden and sharp increase in energy prices and inflation reached record levels (Rudnicka 2024; Verivox 2024). Although these energy costs have fallen again since the fall of 2022, they are still well above the prewar level (as at June 2024). The inflation rate has also slowed to a stable level, but inflation has remained and is noticeable, for example, when buying groceries in everyday life (Federal Statistical Office (Destatis) 2024; Federal Statistical Office (Destatis) n.d.). Such additional costs are a particular burden on low-income households and cause great uncertainty. This is all the more true when trust in politics as a problem solver is damaged, as is currently the case. A significant proportion of the German population between the ages of 18 and 65 show mistrust and resignation towards political decision-makers. Specifically, 73% doubt the competence of politicians, while only 23% have confidence in political processes. Overall, 44% are very worried about their future (Unzicker 2022; Poulakos 2023).

And what is currently worrying the German population? According to a trend study from 2023, 63% of 14 to 29-year-olds are worried about inflation, 59% about war in Europe, 53% about climate change and 45% about an economic crisis. There is also concern about a split in society and a collapse of the pension system. Middle-aged and older population groups have a similar view. However, there are differences when it comes to climate change, which is a greater concern for younger people, and worries about poverty in old age, which is a greater concern for older people (Schnetzer 2023).

A look into the future

Overall, future global development appears to be characterised by a high degree of uncertainty and volatility. On the one hand, our planet urgently requires a continuation of decarbonisation and accelerated implementation of the sustainability transformation. Learned "normalities" and routines will continue to be called into question – sometimes uncomfortably – while new ones need to be tested and practised. It is foreseeable that this will create further stressors (Council of the European Union: General Secretariat of the Council 2024; World Economic Forum (WEF) 2024). Secondly, important elections are due to be held in the EU and beyond 2025 and 2026. Almost three billion people will be called to vote in countries such as Bangladesh, India, Indonesia, Mexico, Pakistan, the United Kingdom and the United States to help determine the new direction of their country. This will show, among other things, to what extent progressive democracies will assert themselves or reactionary, anti-democratic movements will prevail. An expansion and consolidation of reactionary, anti-democratic forces harbours the risk of science-based decisions being displaced in favour of short-term populist agendas (see chapter 2.4). For the relevant supporters, this could lead to a short-term strengthening of their sense of self-efficacy and a moment of relaxation. However, this would (further) delay or even prevent urgently needed transformation measures. This would further exceed socio-ecological stress limits and create a breeding ground for new stressors and worsening crises.

Against this backdrop, the World Economic Forum (WEF) rates misinformation and disinformation as the greatest risk for the next two years (see Figure 12). This is because persistent misinformation widely disseminated through media networks can significantly change public opinion and fuel mistrust of facts and authorities. Disinformation campaigns are usually designed to trigger negative emotions such as fear, anger and insecurity, as they have a wide reach on social media and are remembered for a long time. As a result, public officials, institutions and experts can be perceived increasingly negatively, e.g. as corrupt or incompetent. Misinformation and disinformation thus fuel additional fears and insecurities, undermine trust in democratic decision-making and keep affected citizens in a prolonged state of emotional distress. Confidence and hope for a better future have a correspondingly difficult time. This is particularly important given the tense geopolitical situation worldwide. NATO assumes that hostile intentions of competing state actors will persist. They will seek to “expand their influence by exploiting instabilities and using alternative digital, socio-economic and hybrid means” (North Atlantic Treaty Organization (NATO) 2023).

Similarly, the WEF rates social polarisation as a very high short-term risk (rank 3). Divisive factors such as political polarisation and economic hardship weaken trust and the sense of shared values. The erosion of social cohesion leaves plenty of room for new and emerging risks (Council of the European Union: General Secretariat of the Council 2024; World Economic Forum (WEF) 2024).

In addition to technological and social risks, ecological threats will play an increasingly central role. This is no longer just predicted by environmental activists and researchers. The WEF also considers the risk of extreme weather events to be one of the two greatest threats to the global community in the short and long term (ranked second by 2026 and first by 2034). Other environmental threats are also expected to come to the fore, including critical changes to earth systems, the loss of biodiversity, the collapse of ecosystems and the scarcity of natural resources (World Economic Forum (WEF) 2024).

It becomes clear that – even if decarbonisation and the sustainability transformation pose major challenges for individuals and communities of states – their fundamental necessity for implementation cannot be called into question.

In view of the ongoing crises, widespread concerns and threatening risk scenarios described above, the questions arise:

1. How is the population reacting to the ongoing crisis mode?
2. What strategies have been developed to deal with the ongoing crisis mode?
3. What environmental impact does this have?

Emerging Issues

In Germany’s ever-changing society, which is confronted with complex and often unpredictable crises, various reaction patterns can be observed. Some sections of the population react to the crisis dynamics with withdrawal and avoidance, i.e. a form of resignation. Conversely, other parts of the population are reacting by stepping up their own activities, from climate demonstrations to political rallies on the Russian-Ukrainian war or other geopolitical conflicts to protests against Covid-19 pandemic measures.

The workplace is also increasingly affected by the stress caused by the various crises. The increasing demands and the need to continuously adapt to new circumstances are placing a strain on both individual employees and entire teams and require new approaches to stress management and work organisation.

In view of the growing challenges posed by the various crises, the analysis of private/personal and professional reaction patterns from an environmental policy perspective is becoming increasingly important.

1. Escape from reality: crisis resignation and crisis denial

A profound loss of trust in political and institutional capabilities characterises the reaction of significant

Figure 12

Global risks, sorted by their short- and long-term consequences

Pl.	2 years	10 years
1.	Misinformation and disinformation	Extreme weather events
2.	Extreme weather events	Critical change to Earth systems
3.	Societal polarization	Biodiversity loss and ecosystem collapse
4.	Cyber insecurity	Natural resource shortages
5.	Interstate armed conflict	Misinformation and disinformation
6.	Lack of economic opportunity	Adverse outcomes of AI technologies
7.	Inflation	Involuntary migration
8.	Involuntary migration	Cyber insecurity
9.	Economic downturn	Societal polarization
10.	Polution	Polution

Risk categories
- Economic
- Environmental
- Geopolitical
- Societal
- Technological

Source: own representation according to World Economic Forum (WEF) 2024; p. 8

sections of German society to global crises. A majority, 73%, doubt the competence of political leaders, while only a quarter, 23%, trust political processes. This scepticism goes hand in hand with a feeling of being overwhelmed by current crises, with 59% withdrawing and 87% primarily seeking stability in their private lives. This withdrawal is a clear sign of perceived powerlessness and a belief in the ineffectiveness of one's own actions (Poulakos 2023).

However, the focus on one's own living environment and the associated neglect of global events, including the climate crisis, exacerbates the problem: only 39% of the population actively inform themselves about global events (Poulakos 2023). The decision not to stay informed blocks initiatives for change. In some cases, it goes hand in hand with a negation of the crises themselves. At the same time, withdrawal into the private sphere and a poor level of information about the current situation with regard to the various crises lead to a reduced ability and willingness to react – and thus also to a reduction in the collective ability to act. By prioritising personal withdrawal and avoiding political engagement, parts of the population perceive their own scope for action as irrelevant or ineffective. The challenges posed by crises appear overwhelmingly large and insurmountable, paralysing transformative approaches and the pursuit of sustainable solutions (Novalia and Malekpour 2020).

The aforementioned reaction mechanisms are reinforced by the intensive use of social media combined with the risk of filter bubbles, in which people only see information and opinions that confirm their existing views. This leads to a distorted perception of reality and can further reduce the willingness to engage with opposing opinions. In such isolated spheres of information, the complexity of global crises is often simplified or ignored, which limits the ability for critical reflection and informed action. The emergence of filter bubbles thus contributes to the polarisation of society and makes it more difficult to find collective solutions to global challenges such as the climate crisis (Paris 2011).

Psychological defence mechanisms, such as repression and resignation, protect against massive stress, depression, burnout and similar individual reactions associated with the polycrisis. At the same time, however, these defence mechanisms prevent a direct confrontation with the new, difficult realities. However, the polycrisis not only acts as a source of personal suffering, but can also motivate social engagement, which requires a deeper understanding of these dynamics (Junqueira and Prates 2023).

Solutions include strengthening civic engagement and restoring trust in collective action. The aim is to create conditions that encourage people to play an active role in shaping a sustainable future. The challenge lies in changing the crisis narrative: from a mindset of the ineffectiveness of one's own activities to the recognition of one's own influence and active participation in the creation of a resilient society (Novalia and Malekpour 2020). This statement applies to politics in general. However, it has special significance in the context of environmental policy. In order to be able to respond adequately to environmental problems, it is essential for society as a whole to be able to act. The effective solution to environmental problems is closely linked to a commitment to society as a whole and a sense of self-efficacy in the face of the crisis.

Environmental policy has various starting points here. It can strengthen trust in the system through consistent and long-term strategies and programmes (such as the Climate Protection Act of 2019) and by communicating success, for example through regular reporting. However, strengthening trust in the system also means speaking critical truths and practising transparency, even where developments are critical. One example of this is the yearly climate protection report by the German Federal Government.

It is also important to promote citizen participation and dialogue. Citizens can be involved in decision-making via participatory processes and formats (e.g. citizens' forums, online platforms and local environmental committees). One example of this is the citizen dialogues on the energy transition. These dialogues promoted understanding and acceptance of the energy transition. The conditions for success and possible approaches to successful citizen participation have now been thoroughly researched (Schipperges et al. 2024) so that further steps can be taken here.

Using local points of contact and involving local citizens is also of great importance in the context described above. Participatory budgeting, such as in Freiburg, where citizens have a say in the use of part of the city's budget, often with a focus on sustainable projects, is one option that can be pursued even more in the future – even if its use for sustainable purposes is not guaranteed. However, there are many others, such as better support for community projects within the framework of local energy cooperatives or via neighbourhood initiatives with joint campaigns for nature conservation, waste avoidance, etc.

2. Demand to combat the crisis: increase and intensification of protests

The climate crisis is driving personal engagement, with movements such as Fridays for Future, Extinction Rebellion and Critical Mass, which are characterised by protests for environmental protection and, among other things, by the participation of very young population groups and a strong female influence. The actions of these movements are based on the tradition of civil disobedience, inspired by historical figures such as Rosa Parks and Mahatma Gandhi, with the aim of bringing about sustainable change (Kiesewetter 2022; Haarbusch and Wendt 2023; Rucht 2023b).

Scientists have been continuously pointing out the risks of climate change since the 1970s, but global efforts to combat global warming remain inadequate (Rucht 2023b). Despite 28 UN climate conferences (Federal Government 2023c), global CO_2 emissions have not been reduced to the extent necessary. Against this backdrop, climate and environmental protests have taken on an important role. They specifically draw attention to environmental policy issues and increase the pressure on political decision-makers. Although the direct link between such protests and political decisions is difficult to quantify, historical examples such as the resistance against the nuclear reprocessing plant in Wackersdorf in 1989

(Röhrlich 2019), the prevention of the clearing of the Hambach Forest in 2018 (ZDFtoday 2023) or the partially successful appeal to the Federal Constitutional Court against the 2021 Climate Protection Act have shown that protest movements can bring about significant political change.

Civil disobedience in particular has proven to be an effective method of generating media and public attention. The Fridays for Future actions, in which students strike at school on Fridays, have raised awareness of climate change and specifically the issue of climate justice[31] worldwide. These protests would probably have received less attention if they had taken place outside of school hours. Similarly, the actions of the "Last Generation", who keep the climate crisis in the media through street blockades and similar measures, have drawn attention to the urgency of the issue. Such disruptions to public life often have a more lasting impact on the collective memory than symbolic actions – regardless of the personal assessment of the protest (Rucht 2023b).

The increasing use of civil disobedience in protest movements holds potential for accelerating sustainable transformation, but can also create obstacles. A survey found that 71.4% of respondents believe that actions such as the "Last Generation" street blockades do more harm than good to climate protection, while only 3.6% see a clear benefit in such protests (Civey 2022). The main point of criticism is that these protests often disrupt people's everyday lives without being directly present at the political decision-making venues. In addition, some citizens do not see a conclusive connection between the protest objectives, such as the fight against food waste, and the methods used (Rucht 2023a). The actions against artworks in particular have led to a negative public image of the protest movement, which makes it difficult to attract new supporters (Kumkar 2022).

The tactic of using civil disobedience to put pressure on political decision-makers encourages other groups, including anti-transformation groups, to pursue similar strategies (Theurer 2022). In addition, the media tends to prioritise the form of the protests over their actual cause, which distracts the focus from the core issue of climate protection (Rucht 2023a). Overall, there is also a noticeable wear-and-tear effect of the protests. A change of strategy from Extinction Rebellion – also in response to the political counter-escalation – with the aim of mass mobilisation has been sought since autumn 2023, but so far without any real success (Arnhold 2024).

So while the radical protests of Extinction Rebellion in particular are linked to some problems, it should be noted that media coverage of the protests has increased attention to climate change (Kumkar 2022). Initial studies also show that the protests are having the intended effect on shaping public opinion: After protest actions, concerns with regard to climate change increase across the general population in Germany, and they do not decrease in any population group (Brehm and Gruhl 2024).

From an environmental policy perspective, protests sometimes lend legitimacy to environmental policy measures. However, if they interfere too much in the lives of citizens, there is a risk of delegitimisation. While protests lend expression to a vibrant democracy, they can also make compromises in environmental policy more difficult. However, a successful environmental policy will generally be based on balancing the interests of all parties involved and thus on a broad search for compromise.

In order to absorb the protest movements and use them productively from an environmental policy perspective, it is important to deal with them openly and constructively. Their concerns must be taken on board in one form or another. This starts with entering into a dialogue. Dialogue events between politicians, experts and representatives of protest movements are a starting point here, as are citizens' forums or similar consultation processes.

In view of the climate protests, declaring a climate emergency (as in the United Kingdom, for example) can be a clear sign of a willingness and ability to react in order to emphasise the urgency of action. Stricter environmental laws that meet the demands of the protest movements are ultimately also a strategy for how environmental policy can strengthen protest movements.

31 Among other things, through cooperation with the Verdi trade union.

In addition, lower-threshold but nevertheless effective measures can also be taken in other forms, such as pilot projects that test innovative solutions to environmental problems and involve the community, or the initiation of partnerships between technology companies and NGOs to find innovative solutions for climate protection, as practised in California, for example.

3. Caught in the mood of crisis: the stressed working society

The world of work is undergoing constant change, characterised by high dynamics, increasing uncertainty and growing complexity. At the same time, the ongoing confrontation with multiple crises, such as climate change, the Covid-19 pandemic (with its direct consequences for the world of work), geopolitical conflicts and economic uncertainties is leading to increased stress levels among employees. These stresses affect employees differently depending on their socio-economic status, employment relationship and access to resources, resulting in a differentiated stress situation (Hellert and Stix 2023).

The absenteeism report (Badura et al. 2023) "Zeitenwende – Arbeit gesund gestalten" links the increase in sick days with the increase in stress caused by multiple crises. This observation is supported by a survey conducted by the Pinktum Institute (2024) in which 43.2% of respondents cited the large number of crises as the main stress factor. Companies experience enormous pressure to change, which leads to worries, uncertainties and fears among employees. Such psychosocial stress factors are seen as the cause of more absences due to illness, particularly mental illness, which peaked in 2023 (Boysen-Hogrefe et al. 2023; Deutsches Ärzteblatt 2023; Loschert et al. 2023).

The increase in sick leave and the associated absences from work have reduced the average working hours of employees by 1.3% compared to before the coronavirus pandemic. The average sickness rate rose from 68.2 hours in 2021 to 91.2 hours in 2022 (Boysen-Hogrefe et al. 2023). The possibility of working from home plays an unclear role here, as additional stress may also result from working from home. However, working from home can also lead to stress reduction (German Medical Journal 2022; Chudzicka-Czupała et al. 2023).

In addition, demographic change in Germany is exacerbating the existing labour shortage, which affects economic performance and social welfare (Bauer et al. 2023).

The burden of stress not only affects individual well-being, but also creativity and the ability to innovate, which are essential for tackling the climate crisis and the sustainable transformation of our society. Stress leads to a narrowing of thinking, which hinders the development of creative and innovative solutions for climate protection. In addition, stress reduces productivity, which affects the growth and material prosperity of the economy. Hourly productivity only increased by 0.4% from 2021 to 2022, and a reduction of 1.2% is expected for 2023 compared to 2022 (Bauer et al. 2023).

A functioning and resilient working society is crucial for a successful sustainable transformation. As drivers of innovation, German companies and their workforces play a central role in the development, testing and scaling of green technologies. It is therefore also important from an environmental policy perspective to address the increasing stress levels of employees in companies in order to successfully manage crises, especially the climate crisis (Helmcke et al. 2021).

Environmental policy has various levers to reduce stress in the working society. This starts with setting an example as an employer. The Environment Department can set an example here and create favourable working conditions.

At work, stress reduction starts with the journey to work. Less commuting, promoting more home offices and flexible working hours, green commuter credits that incentivise the use of environmentally friendly means of transport, as well as corresponding tax benefits or changes to existing tax benefits (commuter allowances) are possible measures to make commuting to work less stressful.

Establishing quiet zones in urban areas to reduce noise and light pollution can also help employees find peace and relaxation. Promoting eco-friendly work retreats, i.e. those in natural settings that allow employees to work in a stress-free and inspiring environment, is another environmental starting point. For example, companies could offer regular retreats in eco-villages or nature reserves.

Conclusion for environmental policy and research

The polycrisis is putting increasing strain on our society and jeopardising the transformation towards sustainability. The wide range of reactions to this crisis, including the flight from reality, increasing protest activities and rising stress in the world of work, underline the growing division in society, but also the need for a comprehensive and adaptable environmental policy.

As shown above, many citizens are reacting to the growing personal burden of the coronavirus crisis with a flight from reality and resignation. Environmental policy must address this in order to transform fears into confidence, whereby a high degree of transparency, building trust in the system and conveying an optimistic image of the future are crucial (Suckert 2021). Transparency and trust promote the acceptance of political measures and motivate commitment. Policymakers should therefore strengthen trust in the system, offer positive visions of the future and promote political participation in order to achieve activation and reduce feelings of powerlessness. Transparency, information and appropriate communication, including with those parts of the population that are more difficult to reach, are central to this. The provision of government support to strengthen mental health is also essential (Nadjivan and Sustala 2023).

Increased opportunities for influence are particularly important for those who react to crises with protest activities in order to see their interests represented and feel understood (Bültena 2022). Environmental policy therefore needs ways to constructively interact with protest movements and translate their concerns into political measures in order to achieve broader acceptance and participation in the sustainability transformation.

An overarching perspective that sees times of crisis as an opportunity for innovation and change and promotes a shared understanding (of goals) is crucial for the transformation to a sustainable society. The development and promotion of resilient working models that increase productivity and well-being, combined with a new understanding of welfare, are important steps (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) 2016; p. 36).

2.7 Transformation in economically uncertain times

Trend: The social market economy in Germany is in the midst of a far-reaching transformation towards a socio-ecological orientation. The first important steps have been taken, but considerable investment and efforts are still required. However, the current economic indicators show a stagnating economic situation and do not point to a recovery in the near future. Citizens, companies and the state are all affected by the need for investment. The question of fair distribution is becoming increasingly important. What is the current state of the socio-ecological market economy? What steps have been taken and which have not (yet) been taken? What do tight budgets mean for the transformation?

Emerging Issues

- Transformation when citizens have declining incomes and assets
- Transformation when companies come under increasing economic pressure
- Transformation when the state budget shrinks at all levels

In a nutshell

- Germany can look back on a long period of growth. The post-war social market economy is regarded as a successful model that has brought prosperity to a broad section of society. In view of the Earth's limits, however, it is no longer just a matter of reconciling economic activity with social justice and participation, but also with ecological sustainability. There is talk of a socio-ecological market economy, which is also enshrined in the German government's coalition agreement. This requires a sustainable understanding of prosperity and corresponding framework conditions and investments. But how can these be financed? The German economy is weakening and faces structural challenges. Effective strategies for a new upturn are therefore urgently needed.
- If the current trend of economic uncertainty continues, it will become more difficult for citizens, companies and the state to continue to drive forward the socio-ecological transformation. Even in the current situation, the acceptance of this transformation is already in question because the distribution of the burden is perceived as unfair. If incomes continue to fall or corporate profits decline, this situation may become even more acute. At the same time, declining revenues for the state and companies will mean that insufficient investments can be made in the development of new production and infrastructure or the restructuring of existing systems. On the other hand, declining revenues will potentially reduce the scope for financing innovations – innovations that are essential for the socio-ecological transformation.

Background

Germany is proud of more than 70 years of social market economy. Since the concept was introduced in the middle of the 20th century, the economic and social order has helped many people out of poverty, especially in the post-war years, and has proven to be a successful model for securing prosperity over the past decades (Orth 2023). The concept of the social market economy follows the basic idea of utilising the advantages of a free market economy – such as efficiency and performance – while at the same time compensating for its disadvantages, particularly in terms of social inequality. In short, a state framework should ensure that economic activities serve the welfare of all sections of the. The current German government is striving to further develop the social market economy into a socio-ecological market economy. Economic development should therefore not only take social considerations into account, but also ecological ones. This endeavour is based on the scientifically sound knowledge that an intact ecosystem is a central foundation for prosperity and security (Federal Ministry of Economics and Climate Protection (BMWK) n.d.b; Federal Agency for Civic Education (bpb) 2021; World Economic Forum (WEF) 2024). In a socio-ecological market economy, economic activities must therefore no longer only be socially balanced, but must also be harmonised with planetary boundaries. The needs of both the population and ecosystems must be taken into account. Advancing the sustainability transformation in a socially responsible way is an enormous challenge. Various studies show that Germany needs to invest between 4.5[32] and 6 trillion euros (Burret et al. 2021; Helmcke et al. 2021) to achieve its statutory climate targets by 2045. For the period from 2020 to 2045, this would amount to around EUR 180 to 240 billion per year. At the same time, the population must be involved. Distribution issues and the creation of compensation mechanisms, such as so-called "Klimageld" (climate money), are therefore coming to the fore (Federal Ministry of Labour and Social Affairs (BMAS) 2022; Pokraka 2023).

The state of the socio-ecological market economy

The economic situation of a country is traditionally defined on the basis of indicators such as gross domestic product (GDP)[33] and inflation or price trends. Since 2022, the Federal Economic Report has also taken individual "welfare indicators" into account. They highlight factors such as social justice and participation as well as the management of ecological limits. They therefore represent an important step towards a holistic measurement of welfare, taking into account the necessary sustainability aspects. At the same time, improvements are needed to increase the informative value and applicability of the indicators and to paint a more balanced picture of social welfare. For example, ecological and social indicators should be presented in a much more differentiated way and weighted more heavily (Diefenbacher and Zieschank 2010; Jakob Dirksen 2024).

GDP in Germany was characterised by a decline in the fourth quarter of 2022 and the first quarter of 2023 (Federal Statistical Office (Destatis) 2023b; Wollmershäuser 2023; Federal Statistical Office (Destatis) 2023f). GDP also fell by 0.3% over 2023 as a whole. The Federal Ministry for Economic Affairs expects an increase of 0.2% for 2024 and an increase of 1% for 2025 (Federal Ministry of Economics and Climate Protection (BMWK) 2024; Deutsche Bundesbank 2024).

An annual inflation rate of 2% is seen as a healthy and economically beneficial **price trend**. This increase is considered balanced, as it stabilises the purchasing power of a currency and at the same time provides incentives for investment and consumption. In August 2023, the inflation rate in Germany was 6.1% (Federal Statistical Office (Destatis) 2023d). A decline to 3% is expected for 2024 (Roland Berger GmbH and Handelsblatt Research Institute 2023; p. 27). Looking at the past four years, the price level has risen by around 20% in this period. This development was largely decoupled from wage and salary increases. The purchasing power of citizens has therefore decreased significantly (Federal Ministry of Economics and Climate Protection (BMWK) 2024).

With regard to the development of **social justice and participation**, it can be seen that incomes continue to be unevenly distributed regionally, particularly between the east and west, but also between the north and south. People tend to have more income in the south and west than in the east and north of the country (as of 2021). In addition, the distribution of income among the population has remained rela-

32 The study assumes the goal of decarbonisation in 2050. Bringing this forward to 2045 was not foreseeable at the time of publication of the cited study.
33 Gross domestic product (GDP) describes the value of all goods and services generated in an economy within a year.

tively stable since 2010 and differences have recently decreased slightly (as of 2022). Earnings differences between women and men have also decreased since 2010, but have stagnated since 2020, with men earning on average 18% more gross than women (as of 2023) (Federal Ministry of Economics and Climate Protection (BMWK) 2024).

On the subject of **taking ecological limits into account**, the welfare indicators show, among other things, that greenhouse gas emissions fell from 797 to 750 CO_2 equivalents between 2019 and 2022 and that investments in climate protection measures increased across the board from 2017 to 2019 (Federal Ministry of Economics and Climate Protection (BMWK) 2024). However, Germany is still a long way from achieving “Net Zero” by 2045. Interim targets that have been set, such as reducing GHG emissions by at least 65% by 2030, are at risk of being missed without additional efforts (Expert Council for Climate Issues 2023).

German economy hit by a variety of external factors

In the wake of the Covid-19 pandemic, the European community experienced its worst economic crisis since the Second World War. In Germany, the pandemic led to a severe recession, comparable to the economic slump following the global financial crisis of 2009. Gross domestic product (GDP) fell by 5% (Federal Ministry of Finance (BMF) 2021). Extensive government aid and economic stimulus packages were adopted to cushion the negative impact on the economy and civil society (Federal Government 2023e). In Germany, production sites were primarily affected by disrupted supply chains – a problem that continues to this day. Since then, procurement processes have had to be diversified and additional costs weighed up against security of supply (Ragnitz 2022).

The coronavirus crisis had not yet been overcome when the Russian war of aggression against Ukraine put another damper on the German economy in spring 2022. The intra-European conflict was accompanied by a huge increase in energy prices. In January 2023, producer prices for natural gas were 50.7% higher than in the previous year. Prices for electricity and petroleum products had risen by 27.3% and 12.6% respectively in the same period (Federal Statistical Office (Destatis) 2023e). The sudden loss of Russia as a low-cost supplier of raw materials meant that

Germany's energy-intensive industrial sectors in particular lost a competitive advantage they had enjoyed for years (Wehrle 2023). In addition, although measures to combat high inflation ensured greater price stability, they also led to high interest rates, which had a negative impact on companies' willingness to invest (Federal Ministry of Economics and Climate Protection (BMWK) 2024).

Germany's export orientation means that the success or failure of the economy is particularly dependent on international markets. There are currently two challenges in particular. Firstly, the global economy is only showing weak growth of around 3% and is expected to slow to 2.7% in 2024 (Federal Ministry of Economics and Climate Protection (BMWK) 2024). On the other hand, international competition is intensifying, partly because important trading partners such as the USA and China are heavily prioritising and subsidising domestic production for the domestic and international market. For example, the Chinese government has been very specifically promoting future technologies such as electromobility for years in order to reduce technology dependency on foreign suppliers (Viklenko n.d.). Chinese car manufacturers such as BYD now dominate the domestic market and could oust German manufacturers such as Volkswagen from the future field of electromobility in the face of globalised competition (CAM 2023). In the USA, the Inflation Reduction Act (IRA) was also passed in 2022 to boost the domestic economy and make progress on climate protection. The program aims to support the sustainability transformation through tax credits and subsidies worth around USD 369 billion spread over ten years (Baur et al. 2023; DIW Berlin 2023).

The challenges in the German export business described above are reflected in current sales numbers. In December 2023, Germany's foreign trade recorded a decline of 4.6% compared to the previous year (tagesschau.de 2024a). Exports to the USA and China – Germany's most important trading partners – fell by 9.9% and 12.7% in the same period (tagesschau.de 2024b).

The introduction of the IRA has triggered a debate at EU and federal level on how to respond to the US support programme in order to remain competitive and prevent the departure of important industries (Crawford 2023; German Chamber of Industry and Commerce (DIHK) 2023; German Council of Economic Experts 2023). At federal level, the debt brake enshrined in law has deprived the state of additional scope for investment outside the federal budget and the Climate and Transformation Fund (KTF). The attempt to reallocate EUR 60 billion from the special fund for the Covid-19 pandemic to the KTF was rejected by the Federal Constitutional Court in November 2023 (Wirtschaftswoche 2023). The opportunity to reduce environmentally harmful subsidies on a large scale and reinvest the freed-up funds in the socio-ecological restructuring of the economy has not yet been used by the federal government. The Federal Environment Agency (UBA) (2021) puts the environmentally harmful subsidies at 65 billion euros per year.

Effective strategies urgently needed for economic recovery

The obstacles and challenges outlined so far have hit the German economy very suddenly and could hardly have been foreseen. However, Germany also has to contend with structural problems that have built up over many years. These include high levels of bureaucracy and current and future labour shortages (Federal Ministry of Economics and Climate Protection (BMWK) 2024).

Application, reporting and notification obligations represent an obstacle to growth, particularly for SMEs. They tie up scarce human resources and sometimes significantly delay project progress. The German government therefore wants to review existing information and reporting obligations in cooperation with affected companies to ensure they are appropriate and expedient. In March 2024, the Fourth Bureaucracy Relief Act was passed to ensure more efficient and attractive framework conditions (German Chamber of Industry and Commerce (DIHK) 2024).

The shortage of skilled workers already represents a business risk for more than half of German industrial companies (Statista GmbH 2024c). In the foreseeable future, it is likely to play a more significant role for the economy. The baby boomers are increasingly retiring and too few qualified workers are coming into the workforce. While just under 33,300 training positions remained unfilled in 2012, the number has more than doubled to just under 68,900 unfilled positions in 2022. Currently, technical, social and healthcare professions are particularly affected by the shortage of skilled workers. The former group includes specialists in the fields of sanitation, heating and air conditioning (HVAC specialists) as well as electrical engineering and IT experts, who are of central importance for the transformation of Germany as a business location (KOFA 2023; ver.di 2023). The German government is attempting to counteract this negative trend as part of its skilled labour strategy and with the Skilled Immigration Act. The measures are aimed at integrating more people from Germany and abroad into the German labour market. However, it remains to be seen whether the demographically induced decline in the workforce can be offset; after all, the working-age population will fall by 3.9 million by 2030 and by 10.2 million by 2060 (Federal Ministry of Economics and Climate Protection (BMWK) n.d.).

Enabling transformation through immigration, AI and post-growth?

According to a future study by the Institute for Employment Research (IAB), the potential workforce[34] will shrink by 1.5% even in an optimistic immigration scenario – 400,000 people per year until 2035. In a realistic immigration scenario, which historically assumes an annual net immigration of 200,000 people, there would be a shortage of 2.9 million workers (Klinger and Fuchs 2020; Statista GmbH 2024d). In addition, Germany is not sufficiently attractive for well-educated young people from abroad. Germany competes with countries such as the USA, Australia, New Zealand and the UK, where there is less of a language barrier due to the English language. In addition, Germany is not currently attracting an international reputation for a welcoming culture due to right-wing populist debates and a rise in the polls for right-wing populist parties (Tran 2022).

Due to these challenges, it is also hoped that (generative) artificial intelligence will increase efficiency. However, in order for this future technology to exploit its potential, a corresponding infrastructure and framework must first be developed in the course of digitalisation. This also requires time and skilled workers, which are already in short supply today (Lauterjung n.d.). Furthermore, it is not possible to seriously predict whether artificial intelligence will actually be able to significantly counteract the shortage of skilled workers or whether additional fields of activity and occupational groups will emerge (Klingbeil-Döring 2023). It is also important to ensure that digitalisation is sustainable.

So what would happen if economic growth were no longer possible in the long term due to a lack of potential for increasing productivity? The federal budget would face a continuous deficit and the social system would collapse. Or would there be an alternative? Economic schools of thought, such as degrowth or post-growth theory, offer starting points for this scenario. Both approaches radically question the causal relationship between social well-being and growing GDP. They assume that it is not possible to decouple resource consumption and economic growth, as would be necessary to comply with planetary boundaries. This assessment is also shared by the German Advisory Council on the Environment (SRU). Accordingly, post-growth theory strives for an economy that relies on stable social supply structures and goes hand in hand with a sustainable level of consumption (Petschow et al. 2020b; Petschow et al. 2020a; Thie et al. 2022; German Advisory Council on the Environment (SRU) 2024). However, the welfare state has so far been dependent on economic growth. Services such as statutory insurance, education, public safety and healthcare are cross-financed from tax revenues. Against the backdrop of uncertain growth prospects, the SRU therefore recommends that state welfare systems be restructured in a precautionary manner so that they can fulfill their tasks even without constantly increasing economic output. By implementing a sufficiency-oriented[35] circular economy, an economic model could emerge that is not based on continuous economic growth, but on stability and sustainability. In addition, alternative indicators of prosperity such as quality of life, environmental health and social justice could replace GDP in its position of primacy (German Advisory Council on the Environment (SRU) 2024).

How the German economy will develop in the long term remains to be seen. What is clear, however, is that continuous economic growth cannot always be expected. The following questions therefore arise with regard to environmental policy:

34 The labour force potential is the measure of the maximum available labour supply in Germany. It includes both employed and unemployed people as well as a so-called hidden reserve, i.e. people who are not registered as unemployed for various reasons.

35 In this context, sufficiency-oriented means reducing the consumption of goods and services with harmful environmental impacts. For the SRU, sufficiency is not only a question of individual lifestyles, but also a structural task that requires appropriate political and economic framework conditions. These framework conditions should promote environmentally friendly social practice instead of making it more difficult.

1. How do individual opportunities to contribute to decarbonisation change when citizens have to deal with declining incomes and wealth, and what tasks does this entail for the government?
2. What investments in climate protection and innovations for the transformation can companies make in economically uncertain times?
3. How can government priorities for climate and sustainability policy be set with a shrinking national budget?

Emerging Issues

Socio-ecological transformation is a key challenge for Germany, for citizens, companies and the state. The upcoming and necessary far-reaching change is linked to a broad adaptation of lifestyles and production methods and requires considerable investment in a variety of infrastructures, industrial systems and human capital as well as possible compensatory measures. Structural change harbours numerous risks and opportunities. The question of who will benefit from the transformation and to what extent and who will suffer disadvantages, in particular which social groups will benefit from the redistribution associated with the change and which groups will lose out, will be decisive for the social acceptance of the socio-ecological transformation.

1. Transformation when citizens have declining incomes and assets

In Germany, citizens experienced varying degrees of loss of prosperity in 2020 and especially in 2022 due to inflation and falling real wages. People with lower incomes feel the economic impact of climate policy measures disproportionately, while households with higher incomes are less affected. At the same time, various studies, e.g. Lutter et al. (2022), Oehlmann et al. (2021) and Khalfan et al. (2023) point out that citizens with higher incomes generally cause (significantly) more climate and environmental damage overall, even if they consume more sustainable products and services. This fact raises questions regarding the social balance and fair distribution of the costs and benefits of current energy and climate policy. The “Klimageld” climate money that was actually planned for the current legislative period could be an answer for a fair distribution.

The Social Sustainability Barometer of the Potsdam Institute for Climate Impact Research (2020) confirms the general public’s demand for fairness and justice in the distribution of costs. The energy crisis and geopolitical tensions are strengthening the desire of many for a policy that addresses climate protection and energy supply in an integrated manner. The majority of citizens feel that state support measures are inadequate, especially for people on low incomes, and criticise the perceived unfairness of the cost distribution of measures (Wolf 2020; Roland Berger GmbH and Handelsblatt Research Institute 2023; Wolf et al. 2023). An effective climate policy must include redistribution mechanisms for low-income groups in order to make the transformation inclusive and equitable and thus ensure acceptance of the transformation. Thus Otto et al. (2019) for example, point to greater financial participation by wealthy households in environmental protection measures in order to reduce social inequalities and make the transformation inclusive. Countries such as Sweden show how tax systems with strong progression can distribute the financial burden for environmental protection differently (Otto et al. 2019).

An online survey by the Hans Böckler Foundation (2023) of 2,000 employees from April 2022 also illustrates the fact that the socio-ecological transformation is definitely perceived as an economic risk (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) and Federal Environment Agency (UBA) 2023). While many respondents expect improvements in health (59%), energy security (56%) and air quality (65%), they also fear a higher cost of living (67%), social inequality (51%) and a reduction in living standards (50%). Major obstacles to switching to the “green” economy are potentially lower salaries (40%), the need to relocate (34%) and, at 29%, doubts about qualifications (Schulz and Trappmann 2023). Economic difficulties and rising costs for living and mobility can significantly impair the willingness to actively participate in the socio-ecological transformation (Hickel et al. 2021).

In addition to a declining willingness to support environmental and climate policy measures, falling incomes and wealth also reduce citizens’ ability to invest. Less disposable income means less financial freedom for necessary adjustments in the private sector, such as converting to heating systems based on renewable energy sources or implementing energy efficiency measures in buildings. These financial restrictions therefore limit the active participation of lower-income and normal-income households in the necessary ecological transformation. From this perspective, too, falling incomes and wealth among broad sections of the population, not includingupper income brackets, are therefore problematic from an environmental policy perspective in terms of successfully managing the socio-ecological transformation.

2. Transformation when companies come under increasing economic pressure

The heavily export-oriented German economy was already facing considerable challenges as a result of the Covid-19 pandemic, and recent geopolitical changes are now exacerbating these even further. After ten years of growth, high energy prices, a weak global economy and disrupted supply chains led to a recession in 2020, with GDP falling by 3.8%. The recovery in 2021 with a GDP increase of 3.2% and 1.8% in 2022, despite the Russian-Ukrainian war and energy crisis, was not enough to make up for the losses; GDP was only 0.7% higher than in 2019. For 2023, GDP fell by 0.3%, with an OECD forecast of only 0.2% growth for 2024, one of the lowest among the G20 countries. German industry in particular, which makes a significant contribution to the country's economic output, has been hit hard by the consequences of the pandemic, geopolitical changes and global economic fluctuations (Dohse et al. 2020; Organization for Economic Cooperation and Development (OECD) 2023b; Federal Statistical Office (Destatis) 2023c; Federal Ministry of Economics and Climate Protection (BMWK) 2024; Olk 2024).

More than a fifth of national CO_2 emissions in Germany come directly from industry, particularly from energy-intensive processes such as cement or steel production, where emissions are difficult to reduce with current technologies (Ariadne Project 2023). The transformation to a climate-neutral economy therefore requires not only a switch to renewable energies, but also significant innovations, particularly in energy-intensive sectors. In view of the difficult economic times, the question arises as to whether the investment capacity and innovative strength of companies are sufficient to achieve this.

In 2022, despite economic uncertainties, German companies increased their climate protection investments by 31% to EUR 72 billion (18% in real terms), according to KfW Research (2023) reports. Climate protection measures accounted for 15% of all corporate investments, with a focus on climate-friendly mobility, renewable energies and the energy efficiency of buildings. In response to the energy crisis and price increases, companies not only focused on investing in renewable energies, but also reduced their energy consumption. More than 40% passed on increased energy costs to customers, while only 6% cut back on production. Large companies invested significantly in climate protection, while smaller companies, burdened by uncertainty and loss of profitability, reduced their willingness to invest in this area, tended to favour short-term measures or only made urgent investments to maintain their business. Micro-enterprises financed an average of 42% of their climate investments from their own funds, in contrast to large companies with over 90%. For SMEs, bank loans and subsidies are therefore more important for financing climate protection investments than for large companies (KfW Research 2023).

Despite an increase in transformation investments last year, there is still an investment gap of around EUR 68 billion per year to finance the necessary climate protection measures (KfW Research 2023). Uncertainties about the profitability of climate protection investments and the insufficient internalisation of external costs make it difficult for companies to decide on sustainable investments (KfW Research 2023; Fleiter and Rehfeldt 2023).

As mentioned, achieving climate neutrality by 2045 will require not only investment but also a boost in innovation. However, the innovation push will be hampered by economic uncertainties and deteriorating location conditions (Luderer et al. 2021). Additional problems such as supply difficulties for climate protection technologies and a shortage of skilled workers are exacerbating the situation and threatening Germany's leading role in promising areas of technology (KfW Research 2023). Disruptive changes that require rapid and effective adaptation pose considerable challenges for the established economic sectors in Germany (Ariadne Project 2023; Meyer 2023).

A stable regulatory framework linked to long-term, quantitative and sector-specific targets is needed to make sustainable business attractive. Only then will companies actively participate in shaping a sustainable future and be willing to take risks to develop future technologies such as hydrogen and carbon-capturing technologies. At the same time, the state must support exnovations in order to drive change and make it socially acceptable (Jacob et al. 2019).

3. Transformation when the state budget shrinks at all levels

The Covid-19 pandemic marked a turning point in fiscal policy in Germany and the EU: increased public investment was prioritised to overcome the crisis. To finance these investments, the state increased its debt and temporarily suspended the debt brake. The debt brake, which usually limits net borrowing, requires a post-pandemic reduction in the debt ratio to ensure repayments. However, in view of the socio-ecological transformation and additional crises, the need for high government investment remains, which increases the pressure on fiscal policy (Beznoska et al. 2021; Luderer et al. 2021; Grömling et al. 2022). Germany's public investment is low by international standards, a fact that emphasises the need for a significant increase to promote the green transformation (Organization for Economic Co-operation and Development (OECD) 2023a; Sievert 2023; Wolff 2023).[36] Limited financial scope now threatens to impair not only economic performance, but also transformation capacity.

Limited state investment capacities are a clear obstacle to an effective, future-oriented environmental policy. Germany is faced with the task of investing considerable resources in the socio-ecological transformation, including decarbonising the economy, promoting renewable energy, education, housing and modernising the healthcare sector (Clemens et al. 2019). The need for public investment is estimated at EUR 457 billion over the next ten years (Dullien et al. 2021).

The consequences of limited investment capacity are diverse and far-reaching. A slowdown in the implementation of measures required to achieve climate targets can hinder the transformation to a climate-neutral economy. This entails the risk of initiating the necessary steps to reduce greenhouse gas emissions late or inadequately. In addition, limited investment represents a failure to take advantage of economic opportunities offered by the ecological transformation (Luderer et al. 2021). Investments in renewable energy, energy efficiency and other sustainable technologies can create significant economic growth and new jobs. Failure to realise this potential due to financial restrictions means missing out on growth and job creation (German Council of Economic Experts 2019).

Studies also show that public investment stimulates private investment activity, which is essential for achieving climate protection targets. Every euro of public investment generates an average of EUR 1.50 in private investment, particularly in areas such as education, housing construction and environmental protection (Clemens et al. 2019). A reduction in public investment would therefore not only jeopardise the government's contribution to achieving the ambitious climate protection targets for 2030 and 2045, but would also impair the parallel entrepreneurial transformation efforts (Luderer et al. 2021).

The risk to social justice and public health must also be viewed critically. Essential investments in the health sector and social services strengthen resilience to environmental crises. Neglecting these areas due to financial constraints can exacerbate social inequalities and health risks (Dullien et al. 2021).

Overcoming the challenges ahead requires the reduction of environmentally harmful subsidies and their

36 From 2011 to 2021, Germany only invested between 2.10% (2014) and 2.69% (2020) of GDP in public infrastructure. The EU-27 average was 3.25% in 2021 (Janson n.d.).

redirection, including in the form of a transformation fund for sustainable investment, a reform of fiscal policy that promotes green investment, and the mobilisation of private investment through targeted incentives. A strategic reorientation of financial policy is crucial in order to secure the necessary investments for a sustainable future and to exploit the full potential of the green economy. The Sustainable Finance Advisory Board also has an important role to play here. At the same time, efforts to strengthen the financing of the transformation are already being effectively supported by activities at UN, G7 and G20 level – activities that should be continued in the future.

Conclusion for environmental policy and research

If the current trend of economic uncertainty continues, it will be difficult for citizens, companies and the state to drive forward the socio-ecological transformation without comprehensive changes to current policies. Even in the current situation, acceptance of this transformation is questionable because the distribution of the burden is perceived as unfair. If incomes and corporate profits continue to fall, this situation will worsen. In the spirit of strategic foresight, it is important to prepare for several possible futures and develop strategies on how a transformation can be shaped, even if there is a prolonged recession, e.g. with a low-budget transformation out of the crisis.

It is particularly important to place the social issue at the heart of environmental policy and research efforts. Environmental policy must be socially acceptable and mitigate social hardship. It is crucial that those who cause environmental pollution are held more accountable. The transformation must be made possible for everyone, for example through targeted subsidies for SMEs and energy-efficient refurbishment of rented housing while keeping rents the same. Negative environmental impacts should be reduced and distributed more evenly in order to avoid social injustice. This requires targeted measures to cushion social hardship and ensure that all social groups can benefit from the advantages of sustainable development. Environmental policy must also be intergenerational, taking into account the needs and rights of future generations and ensuring a sustainable livelihood.

The broad range of environmental policy instruments – environmental taxes, subsidy programmes, requirements and permits, etc. – have different distributional effects. When selecting instruments, their distributional effects must be given greater consideration in future and equalisation mechanisms must be taken into account. This is another task for environmental research. It is essential that environmental policy is considered in an integrated manner, i.e. together with social polic taking environmental justice into account. A properly designed environmental policy can help to relieve the burden on economically weaker social groups in particular. Here, we should also actively seek to connect with the current discourse on distributive justice.

As outlined above, falling government and corporate revenues are jeopardising Germany's ability to invest and innovate. However, maintaining competitiveness will also be at risk, as will Germany's technological leadership in many areas. An integrated environmental policy can also contribute to industrial policy. The Export Initiative for Environmental Technologies (EXI), which specifically supports German green tech companies in marketing their innovative solutions internationally, is particularly worthy of mention. The EXI helps companies to open up new markets and thus contributes to the global spread of environmentally friendly technologies, which in turn has positive repercussions for the domestic economy. These approaches to export promotion were largely developed in the Ministry of the Environment.

Various environmental policy decisions have also created the basis for new sectors of the economy, such as photovoltaics and wind power generation. Environmental policy can therefore contribute to Germany's future economic stability and sustainability. Environmental policy in Germany has already written an economic success story in some areas. This should be clearly emphasised through appropriate information work. At the same time, the sustainable industries that particularly benefit from the transformation should be given a greater voice and visibility. Environmental policy itself needs allies in order to push through the transformation, even against the losers of the transformation (e.g. fossil fuel industries). To achieve this, a long-term base of supporters must be created in the economy. Just as ministries have established very close ties with the respective sectors in other policy areas, this should also be pursued more systematically and with a view to the medium-term future in the area of environmental policy.

2.8 Internet of the future

Trend: The internet, a groundbreaking phenomenon of the 1990s, has revolutionised our everyday lives. From digital transformation to powerful artificial intelligence and extended reality technologies, the future of the internet promises a captivating journey through innovation and connectivity: no longer a separate space, but an integral part of our everyday lives. But what exciting twists and turns and challenges will this journey bring for people and the environment? Is the internet currently being completely reinvented? What roles do artificial intelligence and the metaverse play and how could the internet of the future change our relationship with the environment?

Emerging Issues

- New end devices for the internet of the future
- New content: immerse yourself in complex, immersive worlds
- New smartness: internet and artificial intelligence

In a nutshell

- Innovations such as 5G, edge computing, extended reality and artificial intelligence (AI) are paving the way for an Internet of the future that could be characterised by an increasing fusion of physical and virtual worlds. Immersive cyber-physical worlds enable new spaces for experience and interaction with real-time synchronisation. The gaming industry is already reaching an audience of millions in such worlds. In the B2B sector[37], new approaches such as digital factory planning are emerging, and virtual meeting rooms promise new forms of collaboration. The metaverse is considered economically attractive, but there are also doubts regarding feasibility and resource consumption.
- New hardware enables new user experiences and the creation of new content on the internet of the future. At the same time, the need for new devices has a significant environmental impact, especially in terms of the resources used, and the new content consumes considerable amounts of energy in its transmission, calculation and display. However, immersive user experiences also offer the potential to connect citizens with environmental issues in a more impressive way than before.
- Artificial intelligence can have a decisive impact on the creation of complex content for the internet of the future or even make it possible in the first place to the extent that would be necessary for the vision of a metaverse. AI also offers various potentials for developing positive environmental effects in the energy-efficient design of the internet and its

37 “Business-to-business” refers to business relationships between companies.

infrastructure, but these are offset by the considerable consumption of resources by AI applications.

Background

More than 15 years after the introduction of the first ground-breaking smartphones (2007, Apple iPhone) and the subsequent development towards mobile internet, digital networking is constantly advancing. New end devices such as haptic gloves or suits, combined with VR/AR technology, promise immersion in complex, digital worlds that can be experienced with different senses and are being developed by companies at great expense. Probably the best-known example is the Metaverse developed by Mark Zuckerberg's digital company Meta. This is a virtual reality (VR) space that enables users to interact with each other in a computer-generated 3D environment (Peters et al. 2022).[38] In addition, applications based on generative artificial intelligence, such as ChatGPT or Midjourney, are rapidly changing the ways in which the internet can be used and making it more accessible (Jetzke et al. 2019a). Key elements of the internet of the future are already in place today and the corresponding technologies are already available at a high level of maturity (technology readiness level, TR level) (Peters et al. 2022).

Internet of the future as an immersive cyber-physical space

What the internet of the future will look like in detail remains to be seen. However, it is becoming apparent that it could be an increasingly immersive cyber-physical space that is created through the further development and merging of existing and new technologies. The Internet could become "immersive" because the spheres of the digital and analogue worlds, which were previously often viewed separately, are increasingly merging. Current development trends indicate that users of the internet of the future will immerse themselves in cyber-physical spaces with more and more senses than we have experienced on the internet to date. Major tech companies such as Meta (formerly Facebook), Microsoft and Alphabet (formerly Google) have set themselves the goal of shaping such worlds and, with their pioneering achievements and investments, are providing indications of how the internet of the future could develop (Peters et al. 2022).

The internet began with the creation of the first virtual interaction spaces at the end of the 1970s. In the mid-1980s, digital game worlds were explored for the first time with avatars – virtual characters representing the players (Downey 2014). The 1990s saw the international breakthrough for personal computers and stationary internet. ISDN (integrated voice and data network) enabled users to access websites from home for the first time. Online trading began and the age of email communication was born. The 2000s were very much characterised by progress in mobile phone technology. Internet-enabled mobile devices conquered the mass market with UMTS (Universal Mobile Telecommunications System) technology. This was accompanied by a boom in social media such as MySpace, StudiVZ and Facebook. More powerful mobile communications standards such as LTE and 5G are reinforcing the trend, as are the further development of smartphones, user-centred apps with real-time data transmission and other functions such as geopositioning, e.g. Google Maps (Resnick n.d.).

Outlines of the internet of the future become visible

In the further 2020s, these technological foundations are likely to continue to change the internet in the direction of an immersive cyber-physical world:

- Low-latency networks (5G) create the conditions for real-time synchronisation between the virtual and physical world. Latency refers to the time between an event and the subsequent reaction. The shorter the delay, the more real virtual worlds appear to be.

- Edge computing – powerful digital end devices with high computing power – enables data to be collected, stored and processed locally. Computing no longer takes place in central data centres, but increasingly where the data is generated, e.g. on a smartphone. This results in shorter data paths, which increases efficiency and further reduces latency. This forms a further basis for real-time synchronisation (Elmasry et al. 2022).

38 "Metaverse" is not limited to the development of the Meta company. Other companies such as Microsoft and Autodesk are also active in this area and offer their own metaverse worlds. In the following, "metaverse" is used to describe virtual worlds in which users interact through avatars – regardless of the respective developer/provider.

- Artificial intelligence (AI) (large language models, image, object and motion recognition) enables technical systems to capture sensory impressions holistically and respond directly to the individual needs of users. AI is fundamentally based on probability calculation and statistics. Data is collected independently, stored as knowledge, compared with each other, developed logically and used to solve specific problems almost in real time. Modern, generative AI can do more than just automate simple if-then processes (so-called rule-based processes). It is also able to develop independent solutions for complex problems – see ChatGPT text output, for example. Generative AI is getting better and better at imitating human thought patterns. However, unlike humans, AI applications do not have direct access to world knowledge. AI is only ever as good as the data that is available to it for processing through image, object, movement, face and speech recognition (Peters et al. 2022; Seemann 2023).

- Extended reality – which includes augmented reality, virtual reality and mixed reality – enables interactive experiences in computer-generated worlds. Extended reality (XR) is the collective term for technologies that combine immersive experiences with different proportions of real and digital information. In augmented reality (AR), the physical world is enriched with digital information such as images, speech and animation, e.g. Pokémon Go. With virtual reality (VR), users are completely immersed in a digitally simulated environment, for example using the Oculus Rift headset from Meta. Mixed reality (MR) takes you into a world in which physical and digital objects exist side by side and can interact with each other, e.g. using HoloLens 2 glasses from Microsoft.

Physical and virtual living and working environments are increasingly merging

In the business-to-consumer (B2C) sector, immersive cyber-physical offerings are currently highly visible in the gaming sector. The computer game Fortnite reached around 500 million users in 2023 (Tenzer 2024). The 3D game world Roblox reached almost 50 million users per day in 2021. However, cyber-physical worlds in the gaming industry are by no means limited to classic game content. Rather, they also offer musicians digital stages in front of an audience of millions. For example, rapper Travis Scott reportedly reached a good 12 million viewers in 2020 with a virtual avatar performance in the gaming world Fortnite (SPIEGEL Online 2020). Companies are also becoming increasingly present in the metaverse. They have their own virtual stores to generate attention for their brand and boost sales of their physical and virtual products (e-commerce). The online store herrenaustatter.de offers customers the opportunity to virtually explore and try on products in its 3D store. If they are interested in buying, they can choose between cryptocurrency and traditional digital payment methods. Delivery is then processed in the same way as in conventional online retail (Thieme 2022). In addition to gaming, entertainment and e-commerce, the metaverse also offers potential applications in the field of tourism. Users can virtually visit places that are not accessible to them in real life or that should be protected. However, use cases are still rare (Zeit Online 2022; Constantin et al. 2023).

In the business-to-business (B2B) sector, immersive cyber-physical solutions are comparatively less widespread. However, initial approaches and concepts are emerging. For example, BMW and NVIDIA presented Omniverse 2021, a tool that enables fully digital, photorealistic planning of factories. Existing factories are made accessible as digital twins and new factories are planned and simulated completely virtually. Similar tools should enable employees to work together on new products in virtual work environments in the future, regardless of the location of individual people (Autodesk 2022).

The market for virtual meeting rooms has been booming since the Covid-19 pandemic. Collaboration in hybrid teams has become indispensable in large parts of the working world. Established video conferencing software could be supplemented or even replaced by immersive meeting and collaboration rooms in the future. Meta already offers the first virtual working environments in its Metaverse (meta n.d.). New fields of application are also emerging in the education sector. Learners could immerse themselves in virtual learning environments and train assembly work, for example, without wearing out or consuming physical material (Werrlich et al. 2017; WBS TRAINING n.d.).

Metaverse - goldmine or billion-dollar grave?

Some companies see immersive cyber-physical worlds as an economically attractive field of development, particularly under the buzzword “metaverse”. The fact that there is a spirit of optimism in this regard can be clearly seen from the corresponding key figures. From 2021 to 2022, global investment in the development of the metaverse doubled to around 120 billion US dollars (Elmasry et al. 2022). It is striking that large, global tech companies in particular are investing a lot of money to build their own cyber-physical infrastructures, create new markets and occupy them at an early stage.

However, there is no guarantee that current investments will pay off in the long term. There are growing doubts as to whether the futuristic visions of Mark Zuckerberg and other CEOs can actually be realised in practice. It is difficult to assess whether customers and users will see the metaverse as a real added value and adopt it on a broad scale. Like any other innovation, the metaverse has to assert itself against existing offers and routines. But is the interaction experience in metaverse environments really that much better than in conventional, desktop-based digital networks (Hurtz n.d.; Peters 2023)?

A central argument put forward against a foreseeable breakthrough of the Metaverse is that the technology is not yet sufficiently mature. The combination of physical and virtual reality with clunky XR headsets and graphics that do not achieve the expected futuristic quality is a considerable hurdle. Critics also point out that the metaverse currently offers little for the average user that could not be done more easily or better in the real world (Hermann 2022; Rapoza n.d.).

However, if immersive cyber-physical worlds become established, the growth potential is expected to be huge. McKinsey estimates the metaverse market to be worth up to USD 5 trillion by 2030 if extensive business models, products and services can be introduced in the B2B and B2C sectors (Elmasry et al. 2022).

A look into the future

Clear ideas and elaborate scenarios about the possible future development of the internet do not yet exist in this form. Since the 1990s, ideas of immersive worlds have been shaped not least by popular cultural works of literature (such as the 1992 novel "Snow Crash", which describes the metaverse) and film art (e.g. the Matrix films).

The current ideas of a future evolution of the internet towards an immersive, cyber-physical space are primarily shaped by specific sectors.

Potential manifestations of the internet of the future currently differ primarily according to application contexts (Peters 2023). In the area of e-commerce, it is to be expected that the point of sale (POS)[39] will be at the centre of further development. The question here is whether the metaverse will succeed in the long term in creating a shopping experience that attracts a significant number of affluent customers to its virtual stores. It can be assumed that success or failure at this point will depend not least on the further development of digital end devices, the embedding of AI and the graphic quality of XR glasses. The handling of sensitive data is particularly relevant for healthcare (healthcare metaverse) and industry (industrial metaverse). Given the risk of data misuse – for example in the form of deepfakes – what can be shared with a clear conscience? Will patients across society be willing to have relevant health data tracked by commercial providers via wearables – e.g. smart watches, bracelets, rings? This will certainly depend not least on trust in providers and existing data protection guidelines.

The following section deals with the emerging issues of the internet of the future, with a focus on their environmental impact.

1. What impact does the need for new hardware have on the environment?
2. How will content change on the internet of the future, and what opportunities and risks can be identified for the environment and environmental policy?
3. What impact will the trend towards more smartness and AI applications have?

Emerging Issues

In order to participate in the internet of the future, users will need new or improved end devices that enable new content and applications to blur the boundaries between the real and virtual worlds and open up new dimensions of the online experience. The developments outlined above have the potential to have a significant impact on the environment, particularly due to the increased demand for resources and energy

39 POS is usually translated as "point of sale" or "point of sale" in German. It describes the place where a transaction takes place.

for the production and operation of the required devices and infrastructure, as well as the increased data traffic generated by this new, data-intensive content and use cases. At the same time, there are also opportunities and potential that can have a positive impact on the environment.

1. New end devices for the internet of the future

In order to present virtual content so realistically and reactively that interaction with it feels natural, the hardware used must be designed in such a way that information can be passed on to users in near real time and their input can be recorded and processed. To ensure this in connection with online content, a very low-latency network connection must be available (5G network). In addition, the hardware must be powerful enough to perform the necessary calculations to display the virtual content and its reactivity (edge computing).

Many of the technologies that could shape the internet of the future already exist. In the area of end devices, VR/AR glasses and headsets are particularly worth mentioning here, which can be supplemented with additional accessories such as haptic suits and gloves or walking platforms for increased immersion and extended interaction possibilities. These technologies make it possible not only to see and hear virtual worlds and content, but also to interact with virtual objects and environments on a haptic level. Haptic gloves make it possible, for example, to touch and manipulate virtual objects with hand gestures, thereby transmitting haptic feedback to the user's hands. The aim is to create the feeling of holding a real object in your hand.[40] Similar approaches are also being pursued with suits that simulate corresponding sensory perceptions all over the body (Min n.d.). To make movement in virtual worlds as immersive as possible, various manufacturers are now also producing VR running mats or belts. Users can walk, run and jump on these as they would in the real world, and their movements are transferred to the virtual world (Fink n.d.). Increasingly, VR headsets also use eye tracking, which uses sensors to record eye movements. This can be used to calculate high-resolution content more efficiently exactly where the user is looking, but also

40 https://teslasuit.io/

to enable purely gaze-controlled operation of user interfaces and thus contribute to the accessibility of virtual spaces, for example (Adhanom et al. 2023).

Sales of XR hardware are increasing globally: global sales of 22.9 million AR/VR glasses are forecast for 2028, an increase of 259% compared to 2022 at 8.83 million. (Statista GmbH 2024e). The global market for haptic hardware is expected to grow from EUR 10.22 billion (2022) to EUR 23.8 billion in 2030, with an average annual growth rate of 11.4% (Precedence Research 2023). As with other electronic products, the production and operation of XR hardware requires considerable amounts of energy and resources. As the hardware used is generally only partially recyclable or recycled, this development also contributes to the generation of large quantities of electronic waste (Majkowska n.d.). Precise data on the environmental footprint of XR hardware is currently scarce; Meta, for example, states in its sustainability report for 2023 that it has prepared life cycle analyses for its hardware products (meta 2023; p. 30) but has not yet published these. A study conducted by Huawei in 2017 suggests that the use of gold in electronic components and the energy used in production in particular have a negative environmental impact (Andrae 2017).

In addition to new end devices and peripherals, technologies already in widespread use will also adapt to the new developments, which generally involves replacing them with newer models. For example, Vodafone Germany states that 43% of all smartphones operated in its own network will already support 5G in 2023 – in the previous year, this rate was 26%, meaning that a significant number of devices were replaced or connected to the network for the first time (Hassa 2023). By 2028, 5.1 billion people are expected to use a smartphone (Degenhard 2024). In the USA, smartphones are currently replaced after an average of around three years (Statista GmbH 2023c). This short lifespan poses a problem for the environment because smartphones consume considerable amounts of resources and cause emissions during their manufacture (Cordella et al. 2021). As much as 83% of the emissions released for a single smartphone are caused by production, shipping and use in the first year after purchase (Lee et al. 2021). In recent years, there has been a trend towards longer use of smartphones by users (Lee et al. 2021). Longer usage cycles would reduce the need for new hardware and thus the sector’s environmental footprint (Cordella et al. 2021). However, increasing hardware requirements in the internet of the future may counteract this trend and incentivise the replacement of existing hardware – which generates new e-waste, consumes new resources and releases emissions with every smartphone replaced.

In order to make these developments possible, a considerable increase in digital infrastructure is also necessary (transmission masts, data centres, etc.), meaning that the ecological footprint of the new technologies is not limited to the new end devices. In addition to the costs and environmental impact of production, further emissions and energy consumption are incurred for operation. 5G networks generally operate much more energy-efficiently than LTE/4G networks: up to 90% less energy is consumed per transported “traffic unit” (Nokia 2020). However, this effect is negated by an expected rebound effect. Due to the significantly higher required density of the 5G infrastructure and an expected significant increase in traffic (see Emerging Issue 2), it is expected that the energy requirements of the 5G sector could be four to five times higher than those of the 4G network (VIAVI Solutions 2023). Edge computing could help to counteract this development by reducing the amount of data to be transmitted and the necessary server infrastructure – but only if the energy consumption of the now less busy data centres is reduced accordingly (Frąckiewicz n.d.). In addition, although edge computing reduces the computing and transmission power required in the cloud, the distribution of computing power across a large number of end devices with a limited service life (see above) also increases the problem of electronic waste (Frąckiewicz n.d.). Here, too, an increase in the total amount of energy required due to the traffic generated, for example due to increasing user numbers in the metaverse, could significantly exceed the possible energy and emission savings.

In addition to the specific environmental impact, the need for new hardware carries the risk of widening the gap that already exists between those who can afford access to the internet and those whose circumstances make digital participation difficult or impossible (Lacey 2023). This also affects people with disabilities, for example (Glencross et al. 2021) and older people (Mubarak and Suomi 2022). In an increasingly digitalised society, access to the internet is essential for social participation, and non-use leads to serious social and economic disadvantages (Schelisch and Spellerberg 2021). While smartphones have become more and more widespread worldwide in recent years (see Emerging Issue 1) and are giving more and more people access to the internet, a shift towards new, expensive hardware can undo the digitalisation progress of the past and mean that (for the time being) only privileged groups have access to the internet of the future.

2. New content: immerse yourself in complex, immersive worlds

The emergence of new technologies and the availability of devices that open up new usage options will change content on the internet of the future. Faster data transmission and processing will not only allow people to communicate with each other, but also to interact with content in real time. XR technologies make immersion in virtual worlds more realistic than ever before, and innovations in the field of artificial intelligence will also have a significant impact on the content of the internet in the future.

There is a close interaction between the distribution of new forms of content and new hardware: the content outlined above can only be implemented and used with suitable hardware, but attractive user experiences are also a prerequisite for creating sufficient demand on the part of customers and establishing the corresponding hardware on the market. In this context, applications that utilise the unique features and possibilities of the new end devices and can only be used with them are particularly relevant (Lee et al. 2022).

VR content is less suitable for applications that require continuous and precise operation by the user, such as writing texts. Instead, content that can be operated by capturing movements of the hands, eyes and the entire body is more relevant. The use of additional control elements such as game controllers, steering wheels, etc. is also possible. Current hardware-related limitations of VR technology make it particularly attractive for applications that are designed for shorter periods of use, as sessions lasting hours are difficult to implement due to the limited battery power of the headsets and user fatigue (Lee et al. 2022). Future hardware innovations and optimisations could reduce these problems and thus also enable longer use, which in turn influences the content that can be used. Experts assume that XR content will primarily emerge as a hybrid of real-world and digital content in the future. This is not least due to the sensory limitations in purely virtual environments, which cannot be completely eliminated even with new end devices, for example in the sense of taste and smell (Anderson and Rainie 2022; p. 43).

In view of the innovations outlined above, the range of conceivable content is almost unlimited and includes realistic replicas of real objects and environments as well as artistic or commercial creations. In future, for example, furniture stores could offer virtual services that enable people to view new furnishings and furniture in their own home in a three-dimensional and realistic way – including touch tests of new surfaces etc. and a subsequent purchase option within the digital interface. Digital rooms could also be used for meetings between people who are far away from each other, whether in a business or private context. Unlike in conventional video calls, however, participants could experience interactive, immersive content together, such as tours of production facilities, visits to a digital museum, cinemas or a recreated experience of nature (see below).

With significantly higher transmission rates, 5G will ensure that the trend towards high-resolution video, music and other streaming content continues and develops towards completely load-time-free user experiences (Arora n.d.). The combination of low-latency transmission and high computing capacity of edge computing devices also enables providers to deliver highly personalised and reactive content to users (Arora n.d.). This content can be consumed collaboratively or used interactively in real time (Cherukuri n.d.). It is assumed that globally, the average data consumption per smartphone will increase from 21 gigabytes/month (2023) to 56 gigabytes/month in 2029; the global monthly throughput of mobile data is expected to increase by a factor of around three from 130 exabytes[41] in 2023 to 403 exabytes in 2029 (Ericsson 2023). An increase due to the increasing use of XR is already factored into this forecast: if the growth of the XR market exceeds the assumed level, a correspondingly stronger increase in mobile data

41 One exabyte corresponds to 1,048,576 terabytes or 1,073,741,824 gigabytes.

usage is to be expected (Ericsson 2023). Although the 5G network is more energy-efficient than previous transmission technologies (see above), such an increase in data volumes could ultimately lead to a significant increase in energy consumption compared to the present – along with the associated environmental impact.

Given its immersive, attention-grabbing nature, metaverse content carries the risk that users are more likely to find disinformation credible (Peters 2023). In the environmental context, this can make the success of the sustainability transformation more difficult if, for example, content misrepresents scientific facts, casts climate and nature conservation measures in a false light or discredits people who are committed to environmental issues (see chapter 2.9). However, the immersive nature of the medium can also be used to communicate environmental issues (Spangenberger et al. 2022; Meijers et al. 2023; Newton et al. 2023; Thoma et al. 2023; Yavo-Ayalon et al. 2023). Various options are conceivable here:

- Extended reality makes it possible to experience the earth's nature immersively, regardless of the user's location. This approach can awaken empathy and increase the motivation to protect the environment through one's own actions. The company "Habitat XR", for example, offers XR tours through various habitats and enables digital encounters with rhinos in Chad, gorillas in Rwanda or armadillos in the Kalahari Desert.[42] To a certain extent, such experiences could also replace or supplement real vacation trips and save emissions (Lee et al. 2022).

- XR is already being used today to bring scenes from the past to life (Barbara 2022). In this way, the problem of the "shifting baseline syndrome" can be countered. Increasing environmental degradation leads to the social expectations of an acceptable state of nature shifting further and further downwards – members of each new generation accept the conditions they find as normal, even if these are already degraded (Soga and Gaston 2018). Extended reality can be used to represent the state of nature at earlier points in time, so that, for example, 20-year-olds today can experience an environment in which no more than 75% of the biomass of flying insects has disappeared (Hallmann et al. 2017). This brings abstract statistics about the state of and changes to our planet to life and emphasises the urgency of taking decisive action against climate change and species extinction.

- Finally, XR can also be used to make people aware of the dangers of climate change by modelling the forecasts of known climate models, e.g. the IPCC, in plastic experience spaces. Yavo-Ayalon et al. (2023) for example, showed residents of Roosevelt Island (New York, USA) models of possible flooding in VR and were subsequently able to measure an increased awareness of the dangers of climate change and a higher motivation to take countermeasures. In the future, such experiences could be generated for a variety of locations and made available online.

In addition, the possibilities of targeting individual users through personalised content could also be used for environmental education, in addition to economic use through advertising etc., in order to convey messages and instruments of environmental policy (German Advisory Council on the Environment (SRU) 2021) to individual citizens more effectively than before and to raise awareness of environmental policy issues. In the future, the use of AI tools can reduce the effort required to create such content and enable further dissemination (see Emerging Issue 3).

However, these opportunities are offset by the considerable energy consumption of the technology and the aforementioned resource requirements of the necessary hardware, which must be purchased in order to use the internet of the future. In the long term, greater adaptation of immersive virtual worlds based on AR and VR could also lead to a massive increase in the computing capacities required for cloud and edge computing. Individual figures from the IT industry estimate an increase in the required computing capacities by a factor of one thousand (Peters et al. 2022). In addition, experts attest that the metaverse poses a number of risks that could also impact the environment in various ways. For example, virtual reality could lead to alienation from the real environment

42 https://www.habitatxr.com/

and thus inhibit rather than strengthen motivation for environmental protection measures; the technical framework of the metaverse also enables actors working against climate protection to exert influence and place credible but misleading content (see above); and, as with other social networks, the metaverse could also be used to further polarise society and thus burden political decision-making processes towards greater environmental protection (Anderson and Rainie 2022).

3. New smartness: internet and artificial intelligence
The presence of AI-generated content will also have a significant impact on the internet of the future. This content will become increasingly difficult to distinguish from human products such as images, texts or videos and poses a significant risk of disinformation (see chapter 2.9). At the same time, the widespread use of AI offers the potential for a significantly different user experience on the internet, including AI-supported search, content generation and support for various tasks.

With the introduction of ChatGPT in November 2022, AI applications quickly became a hotly debated topic in society and found a broad base of users (Albrecht 2023b). It also quickly became clear in the public consciousness that AI would fundamentally change the use of the internet, but also human-machine interactions in general – with an impact on almost all areas of life (Delcker 2023). Experts are forecasting strong growth in the global AI market: while the market was worth USD 95.6 billion in 2021 (before the ChatGPT hype), the forecast for 2030 is almost USD 2 trillion – an almost twenty-fold increase in turnover (Thormundsson 2023).

AI-supported online searches are currently one of the most important applications of AI. At first glance, this is a valuable aid for users: for example, AI can identify the core of the question from imprecise queries, search for it specifically and thus generate better results. In addition, results are summarised in a compact form, which saves research effort and time. However, due to its mode of operation, LLM[43] predicts word sequences and has no understanding of the content of the processed information – AI is also susceptible to generating false information; the generation of incorrect content by AI is referred to as a "hallucination" (Kanana n.d.). Users must be aware of this danger when using AI tools in order to enable responsible use and minimise the risk of false information.

43 LLM = Large Language Model; computer model that has been trained to process linguistic data (e.g. ChatGPT) (Albrecht 2023b).

Another important area is the creation of content using AI, be it images (Dall-E, Midjourney), texts (ChatGPT, Bard, Bing) or videos (DeepBrain AI, Synthesia.io). AI-supported tools enable the creation and illustration of texts in the shortest possible time, for example, and thus lay the foundation for a wide range of applications on the internet of the future – from advertising and online journalism to sophisticated cyberattacks that are difficult to recognise at first glance, such as phishing and social engineering (see chapter 2.9) (Kanana n.d.). The accelerated generation of content using AI also enables providers to fill huge virtual worlds such as the metaverse with appealing content – a prerequisite for their success with users (Lv 2023). However, realistic-looking AI products can also be used to discredit individuals and groups through false information (Engler and Dhamani n.d.); in the environmental field, for example, climate activist Greta Thunberg has already been the victim of such attacks (Bart 2023). The increasing spread of AI therefore also provides opponents of climate and environmental protection measures with new tools to delay or prevent a sustainable transformation by influencing political opinion (see chapter 2.4 and 2.9).

Compared to other applications on the internet, AI models perform significantly more complex calculations to generate their results. This is associated with considerable energy requirements. In particular, developments in the field of generative AI, e.g. ChatGPT, and immersive worlds such as metaverse are likely to increase global resource consumption in the foreseeable future if they spread dynamically. The scope of this development can already be glimpsed today: search functions supported by generative AI, for example, are ten times more energy-intensive than conventional search engines (Albrecht 2023b). In view of the predicted market growth of AI applications, a drastic increase in energy consumption and the associated emissions can therefore be expected.

However, the use of AI applications in conjunction with the internet and online services can also have positive environmental effects. Google claims to use AI for fuel-efficient route planning in Google Maps (tagesschau.de 2023b). As early as 2016, the use of AI reduced the energy consumption for cooling Google's own data centers by 40% (Evans and Gao 2016). AI can also be used to optimise websites and applications in terms of their resource consumption. For example, AI-based image compression applications can reduce the file size of images on websites without compromising their visual quality, thus saving energy on the server side and during data transmission (Caballero 2023). AI applications that recognise which type of AI model is best suited for a task have the potential to avoid unnecessary calculations and thus reduce energy and emissions (Cho n.d.). In combination with other environmentally relevant applications, for example for process optimisation and energy saving in complex industrial and logistics facilities such as container ports (Tsolakis et al. 2022), the use of AI could lead to a reduction in greenhouse gas emissions of 6.1% in the USA and 4.9% in Europe by 2030 (Thormundsson 2022).

Conclusion for environmental policy and research

The developments outlined above have a number of implications for the environment. On the one hand, they can lead to an exacerbation of existing environmental impacts in the electronics sector, such as resource and energy consumption in the production and use of new end devices and the generation of electronic waste during their disposal. On the other hand, they also offer new opportunities to promote environmental issues and sustainable practices, for example through the use of XR content for environmental education or through AI optimisation of industrial processes.

An environmental policy assessment of the internet of the future requires a detailed, transparent monitoring of the environmental impact of all relevant technologies. The existing research and information gap must be closed in order to comprehensively assess the opportunities and risks of the new technologies against the background of their environmental impact.

An environmentally-oriented approach to the internet of the future must therefore include a series of measures that enable the use of existing potential and also weigh up the risks to the environment and take regulatory action. Corresponding measures could include promoting the development of more energy- and resource-efficient hardware (or minimum requirements to be increased over time or bans on obsolete/non-efficient hardware), the demand for repair options and offers as well as recycling methods for electronic waste and the use of renewable energy sources for the operation of the technologies. One example of this is the Ecodesign Regulation, which

came into force in the EU in 2024 and enables the introduction of ecodesign product guidelines, for example with regard to durability, reusability, reparability and environmental footprint (European Commission (EC) 2024) and will therefore also affect the new end devices of the internet of the future.

In terms of society as a whole, the internet of the future may further exacerbate existing problems of digitalisation, be it through a further shift of retail trade from town centers to XR-supported online trade, including the resulting consequences for town centres, such as vacancies and a reduction in the quality of stay and quality of life (Hangebruch 2023), or through even more sophisticated misinformation (see Emerging Issue 2) and a widening digital divide (see Emerging Issue 1). These problems must also be taken into account when setting the course for an internet of the future that focuses on environmental consequences and promotes the transformation to a sustainable society instead of hindering it.

2.9 Cybersecurity and environmental protection

Trend: In a comprehensively networked world, there is an increasing risk of being exposed to attacks via the internet. These can range from the spread of fake news via politically active individuals to the technical paralysis of entire institutions, companies, or infrastructures. What are the consequences, particularly in view of the increasing vulnerability of critical infrastructures, corporate and administrative activities and individuals? How can such attacks affect society's transformation efforts and what are the consequences for environmental protection?

Emerging Issues

- Attacks on (critical) infrastructures
- Attacks on companies and value chains
- Attacks on political institutions
- Attacks on the formation of opinion

In a nutshell

- The increasing networking and complexity of information technology poses challenges in terms of making systems secure and protecting them from cyberattacks, while the number of cyberattacks continues to rise. Attackers use a variety of methods and aim to blackmail businesses, government and individuals spread disinformation or sabotage critical infrastructures. In the future, the use of new technologies such as AI may present new challenges as well as opportunities to reshape cybersecurity.

- Cyberattacks can have a variety of effects on the environment. Attacks on critical infrastructure can lead to accidents and associated environmental damage, for example through the release of pollutants. Attacks on the production of transformational technologies hinder environmental progress, and cyberattacks on environmental authorities hinder the effective protection of the environment. In addition, online attacks on the credibility of politically active individuals and groups also undermine the social consensus for environmental protection measures, which is the basis for political action.

- In view of increasing networking and ever more diverse opportunities for cyberattacks, the focus of cybersecurity is shifting towards resilience, i.e. minimising the damage in the event of an attack. This includes emergency precautions (redundant systems, etc.) for critical infrastructure and in value chains, but also information and media education for users and the public, e.g. to identify misinformation. This focus can form the basis of a cybersecurity strategy for the environmental resort.

Background

The digital transformation with ever more networked information technology (IT) and increasingly digitalised, socially relevant infrastructures is shaping our everyday lives. It is difficult to imagine life without digital technologies. Our social and economic dependence on functioning IT systems is particularly evident when they are no longer available, for example due to attacks: e.g. when a cyberattack on satellites at the start of the Russian war of aggression against Ukraine caused the remote maintenance of wind turbines to be suspended (Brühl 2022) or when the entire communications infrastructure in the Gaza Strip collapsed.

Advancing digitalisation and networking, as well as the increasing complexity of IT systems, offer ever greater opportunities for attacks, while criminal methods and systematisation of hacker attacks continue to develop. Vulnerabilities and attacks in the digital world have potentially serious consequences (Federal Ministry of the Interior, Building and Community 2021). Both politically motivated cyberattacks such as election manipulation and criminal hacker attacks aimed at extorting ransom money, for example, can have a negative impact on people, organisations, state institutions and even entire societies. These diverse attacks target, for example, supply chains, corporate production or healthcare and energy supply and other critical infrastructures.

This increases the relevance of cybersecurity for all social stakeholders. The German Federal Office for Information Security describes cybersecurity as dealing with "[...] all aspects of security in information and communication technology. The field of action of classic IT security is thereby extended to the entire cyberspace. This encompasses all information technology connected to the internet and comparable networks and includes communication, applications, processes and processed information based on it." (Federal Office for Information Security (BSI) 2022a; p. 16). The German Cybersecurity Strategy distinguishes between three types of cybersecurity threats (Federal Ministry of the Interior, Building and Community 2021). Cybercrime, e.g. to extort ransom money; cyberattacks, such as state/politically motivated attacks or cyberterrorism with the aim of causing fear or panic; or hybrid threats such as cybersabotage, disinformation campaigns and cyber espionage.

The number of recorded cyberattacks in Germany in 2023 was 134,407 (Federal Criminal Police Office 2024). Although there was a slight decrease of 1.8% compared to the previous year, the number of attacks has risen continuously over the years. However, these absolute numbers do not paint a realistic picture of cyberattacks, as they only include cases in which both the attackers and the damage were recorded in Germany alone. This picture is also confirmed by the "BSI Situation Report" 2023, which shows that the data on attacks from abroad in particular has been steadily increasing since 2020 – the year in which the records began. Furthermore, it is estimated that only 10% of cases are actually reported – the number of unreported cases is therefore potentially very large (Federal Office for Information Security (BSI) 2023b).

Attacks on cybersecurity affect the economy, society and individuals

The majority of cyberattacks in Germany affect economic players. There is a connection between the digitalisation efforts in and since the Covid-19 pandemic and an increase in attacks on companies. This is due to the fact that lockdowns necessitated a rapid switch to virtual working and therefore many additional digital interactions were conducted via private infrastructures. According to one estimate, the damage caused by cyberattacks to the German economy will amount to 202.7 billion euros in 2022 (bitkom Research 2022). A total of 63% of the representative companies surveyed reported the theft of sensitive data, 55% reported sabotage of digital systems and 57% reported spying on digital communication.

But the state and administration are also targets of attacks: for example, all IT systems of a district administration in Saxony-Anhalt were paralysed in July 2021. As a result, Germany declared its first digital disaster in February 2022. The incident particularly affected local administrative processes close to citizens, such as the payment of social benefits (Heidtmann 2021).

However, critical infrastructures in the energy or transportation sector or institutions in the education or healthcare sector are also targeted. The "BSI Situation Report" (2023b) describes so-called "advanced persistent threats" as long-term attacks that are planned with great effort. They are often very elaborately aimed at sabotaging or obtaining information from major players and are becoming increasingly important as an attack scenario, especially against the backdrop of geopolitical tensions. Government institutions and NGOs, as well as the energy and pharmaceutical sectors and the arms industry, are increasingly becoming targets. This shows just how vulnerable critical infrastructures are. It is interesting to note the growth of the cybercriminal shadow economy, which is making more and more services and specialised tools available for such attacks (Federal Office for Information Security (BSI) 2023b).

Sabotage attacks on media or individuals, such as Annalena Baerbock, with the aim of discrediting or spreading disinformation, can be used as examples of cybersecurity attacks (Hate Aid 2022). The election of Donald Trump in 2016 and the Brexit referendum were linked to unreliable and misleading information (Hoffmann 2023). In a more recent case, pro-Russian hackers are said to have attempted to demoralise Ukrainians in Europe with a campaign. According to information from an IT security company, the hackers also used domains related to Alexei Navalny (Kolvenbach 2024). Such attacks can have a significant impact on the formation of public opinion and trust in information and the institutions and individuals allegedly disseminating it.

These examples illustrate that attacks can affect economic and state actors as well as critical infrastructures, but also society and individuals. At the same time, all stakeholder groups are highly interconnected systems with interdependencies.

Diverse forms of attack and the role of networked systems and AI for cybersecurity

The interaction of complex systems and complex software that are insecure or incorrectly configured provides more and more gateways for attacks. The actual use of software and the people who use it can also mean additional critical vulnerabilities. Various forms of attack with different threat scenarios can be classified into these gateways (Federal Office for Information Security (BSI) 2023b).

- Ransomware attacks are mainly aimed at extorting ransom money. Here, data is encrypted in such a way that it can only be made usable again by paying what the blackmailers demand.
- Denial of Service (DoS) and Distributed Denial of Service (DDoS) attacks aim to overload or disrupt information systems by flooding servers with a large number of requests. There are various forms of attack, for example by sending so many emails that email accounts and servers collapse. In DDoS attacks, a particularly large number of network resources can be attacked at once using distributed computers.
- In supply chain attacks, the software products of suppliers and manufacturers are infiltrated, which are then downloaded or used by the targets that are to be attacked. Attackers thus infect the entire network via the organisation's supply chain. This can result in highly sensitive data being tapped or systems being paralysed; ransomware is also conceivable.
- Malware is used to infiltrate the systems of attack targets in various ways. This can take the form of Trojans – malware disguised as a useful program – viruses (an infection with the malware in the background of a host program) or "worms", malware that can run independently. Infected devices can be expanded by cybercriminals into botnets, in which devices networked via the internet are also infiltrated. This also leads to compromised data and systems or can trigger ransom demands.
- More than half of the emails sent worldwide are spam. Spam can not only contain advertising, but can also install malware via email attachments or contain phishing or disinformation dissemination ("hoax"). Phishing is often aimed at spying on personal data and passwords.
- Attackers can also use doxing and data leaks to access identities and relevant passwords. Doxing describes the collection and public disclosure of previously collected and personal data.
- In social engineering methods, attackers exploit human characteristics and emotions such as fear or time pressure to access desired data in a similar way to fraud. There are many ways in which compromised data can be used: access to financial services is often spied on, or money is attempted to be transferred.

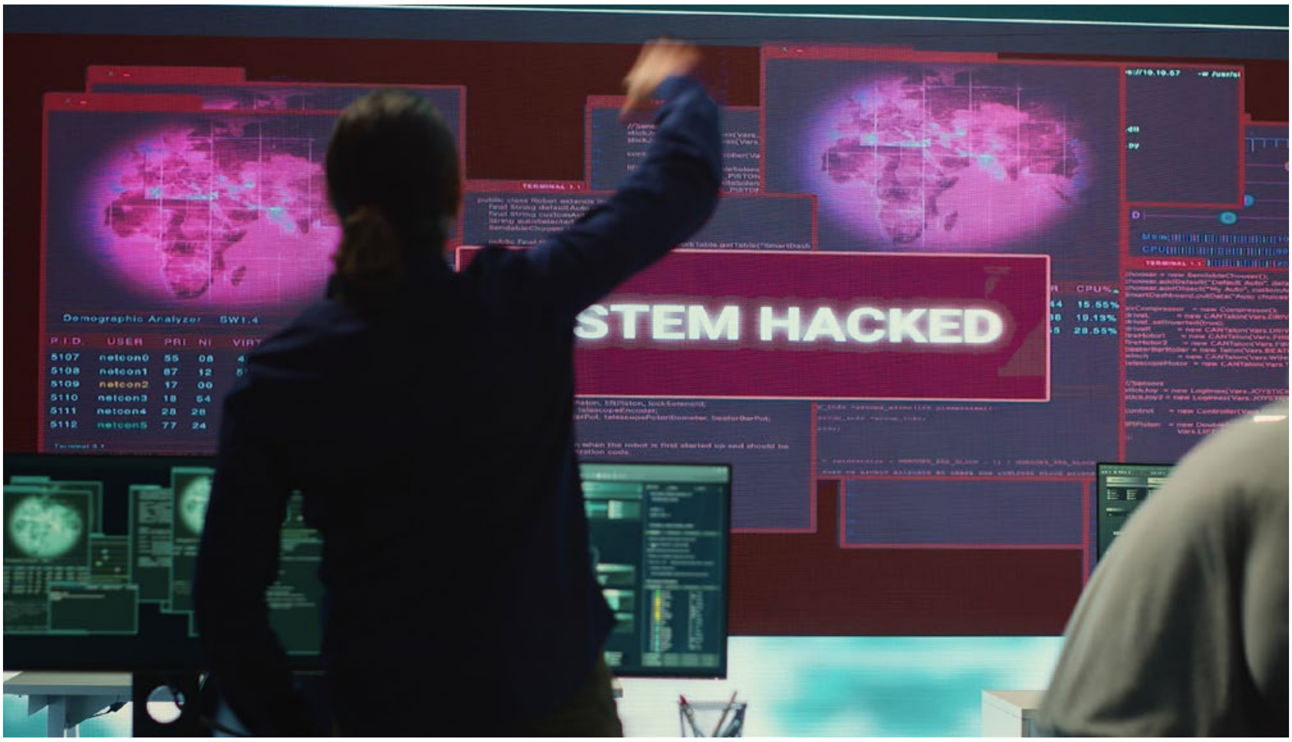
Ransomware is the most common form of attack recorded (Federal Office for Information Security (BSI) 2022b; Federal Office for Information Security (BSI)

2023b). Attacks and corresponding blackmail mainly affect companies. While forms of attack often target state or organisational actors, individuals are also victims of cybercrime. More than one in four people in Germany (29%) state that they have been a victim of cybercrime; cases of online shopping fraud or unauthorised access to an online account are particularly common (Federal Office for Information Security (BSI) 2023c).

The top threats per target group are described by the Federal Office for Information Security (BSI) (2023b) accordingly for society with identity theft and phishing, for the economy with ransomware and supply chain attacks and for government and administration with ransomware and advanced persistent threats.

With attackers and economic players operating on a global scale, the protection of IT systems and networks is increasingly becoming a global challenge with global implications. This also becomes clear when looking at current international political developments: in September 2023 alone, the American Center for Strategic and International Studies registered 16 cybersecurity incidents that are politically motivated (Center for Strategic & International Studies 2023). Space security and attacks on IT technology that affect cyberspace are also playing an increasing role in the consideration of cybersecurity (Stockholm International Peace Research Institute (SIPRI) 2023).

When looking at the forms of attack and the networking of systems, it becomes clear that not only one target is attacked by the forms of attack outlined, but that the actors concerned are often connected and chain reactions result from the networking. Combined with ongoing technological developments and the increasing complexity and networking of systems, this also brings with it new emerging threat scenarios and challenges. This is exemplified by the consideration of intelligent networked objects (Internet of Things). Security risks increase when infected systems can easily connect via the networking of objects and can be misused via this network – through so-called botnets (Federal Office for Information Security (BSI) 2023a). Current developments in the use of neural networks and machine learning with regard to artificial intelligence and generative artificial intelligence are also creating new challenges for cybersecurity: for example, automated attacks can be launched or deepfakes spread, in which photos or videos and text are deliberately manipulated in order to spread disinformation. At the same time, however, there is also the potential to use artificial intelligence to automatically build more secure systems and identify gaps (Golden and Johnson 2017; Sabin 2023).



A look into the future

Attacks on cybersecurity in various areas are becoming more frequent, and the types of attack and targets are becoming more diverse and efficient. In particular, the market for criminal actors is growing and methods are constantly evolving with new technological possibilities. For example, the availability and use of generative artificial intelligence (AI) have triggered an increase in organised phishing campaigns ("phishing as-a-service") (Federal Office for Information Security (BSI) 2023b). These developments are expected to have a particular impact on professional shadow economy services. New business models are constantly emerging, such as that of the "initial access broker", who sells knowledge about access points (obtained e.g. via phishing or vulnerability knowledge) to third parties.

While AI is increasing the quantity and quality of cyberattacks, new technological developments also offer opportunities to uncover security gaps and detect attacks. Companies and state actors are reacting and positioning themselves to take appropriate measures. German companies, for example, are spending more on cybersecurity (bitkom Research 2022). Nevertheless, the cybersecurity strategies of many companies have so far been purely preventive and have not adapted to the increasing number of various attacks with appropriate measures and reactive emergency plans (Mair et al. 2023).

Cybersecurity will become increasingly important for all players in social and economic life in the future. In particular, companies or government organisations that use and offer digital, networked systems and complex software as well as manage critical infrastructures or supply chains will be required to deal more intensively with aspects of cybersecurity in the future and invest more in the field. This could turn cybersecurity from a "hygiene factor" into a differentiating factor for companies (Mair et al. 2023).

At the same time, however, the dependence on global regulations and international governance structures is repeatedly pointed out. Gartner predicts that countries will adopt more extensive regulations in the future in order to better combat cybercrime such as ransomware extortion (Kolaric n.d.). Geopolitical influences will also play an increasingly important role in the context of cybersecurity and it is expected that hostile actors will not only sabotage, but also use technology environments as a weapon (see chapter 2.5) (Kolaric n.d.). Individuals will increasingly be required to develop security skills to recognise attacks or media skills to expose disinformation campaigns. New insights should also be gained through targeted research funding programs such as the announcement "Trust in Democracy and the State: Identifying and Countering Digital Disinformation" as part of the research framework programme "Digital. Secure. Sovereign." (Federal Ministry of Education and Research (BMBF) 2022). Wirnsperger et al. (2020) describe the two aspects a) integration of cybersecurity in (emerging) technologies and b) global cyber power relations as key drivers for the development of future cyber risks. They also emphasise the ever-increasing dependence on the networking of systems and global players.

These developments give rise to questions that are becoming increasingly relevant. What role do attacks on critical infrastructure, companies and value chains, but also attacks on political institutions or individuals, for example via disinformation campaigns, play with regard to sustainability? What will these developments look like in the future from the perspective of global sustainability and what role do not only ecological but also social aspects play here (see chapter 2.4)?

Emerging Issues

Germany was the scene of a series of far-reaching cyberattacks in 2023: in October, the municipal IT service provider Südwestfalen-IT was hacked, resulting in the IT infrastructure of 72 municipalities in North Rhine-Westphalia going down; during the same period, Frankfurt University Hospital was also the target of a hacker attack. In both cases, the operation of the affected facilities was severely restricted, with the hospital yet to fully recover (Müller 2024). Cyberattacks have increased significantly in recent years, partly as a result of the digitalisation driven by the Covid-19 pandemic. There is an increasing number of actors who have the will and the capacity to carry out such attacks (Möller 2023). These not only have serious and costly consequences for companies, but also directly threaten the functioning of critical infrastructure, affect public services and, in some cases, target the formation of public and democratic opinion. Cyberattacks can also lead directly to environmental damage or have indirect environmental impacts.

1. Attacks on (critical) infrastructures

According to the Federal Office for Security and Information Technology Act (BSIG), critical infrastructures include "facilities, installations or parts [...] belonging to the energy, information technology and telecommunications, transport and traffic, health, water, food, finance and insurance and municipal waste disposal sectors that are of great importance for the functioning of the community because their failure or impairment would result in significant supply bottlenecks or threats to public security" (BSIG Section 2, paragraph 10; German Bundestag 2009).

Attacks on critical infrastructure have occurred repeatedly in recent years. Since the beginning of Russia's war against Ukraine, there has been an increase in targeted acts of sabotage against critical supply infrastructures in Europe (Pawlak 2023). Examples include the blowing up of the Nord Stream gas pipelines in the Baltic Sea (Sanderson et al. 2023), the damage to submarine cables off Spitsbergen (Staalesen n.d.) and in the Mediterranean (King n.d.) and the sabotage of the Deutsche Bahn train radio system (Deutsche Bahn 2022). Since 2023, there has been an increase in disruptions to the GPS tracking system in the Baltic Sea region, which affect shipping and air traffic and are seen by investigators as hybrid war tactics by Russia (Möller and Strüber 2024). In late 2023, it was also revealed that the UK's Sellafield nuclear power plant had been the subject of a year-long cyberattack in which information on sensitive activities, e.g. the transportation of radioactive waste or the monitoring of leaks of hazardous material, was presumably tapped (Isaac and Lawson 2023).

Such attacks can have a significant negative impact on the environment. Critical infrastructures are often located in the immediate vicinity of natural areas, such as power plants with large cooling water requirements or wind farms (Couce-Vieira et al. 2020; Pawlak 2023). Direct damage aimed at weakening or permanently destroying such infrastructure through sabotage or cyberattacks can therefore result in serious environmental impacts. The blowing up of the Nord Stream gas pipelines has, according to Sanderson et al. (2023), stirred up more than 250,000 tons of toxic sediment and released large quantities of methane gas. It is not only the direct destruction of critical infrastructure that poses risks here. Past incidents have shown that gaps in the digital security architecture can also lead to environmental damage through individual attacks. In 2000, for example, a hacker attack on a sewage treatment plant in Australia resulted in the release of over 800,000 litres of untreated wastewater (Sayfayn and Madnick 2017; Couce-Vieira et al. 2020).

Despite these known risks, critical infrastructures are often still vulnerable to attacks. In particular, critical infrastructure in maritime environments is currently often inadequately protected against deliberate damage (Pawlak 2023). However, urban infrastructures with direct contact to environmental media, such as sewage and water treatment plants, are also often vulnerable to attacks (Demmig 2020). The example of Sellafield mentioned above shows that even a nuclear facility that has already been the scene of the most serious nuclear incident in British history in the past (Isaac and Lawson 2023) was inadequately secured against cyberattacks.

Alongside protection against physical attacks, cybersecurity is the most important form of protection for critical infrastructure. This is highly necessary as critical infrastructure is usually highly technical and networked. In many industries, complex networks of sensors monitor and control the functioning of systems, for example the flow of pipelines, the water level in reservoirs or the gates that retain and discharge wastewater (Couce-Vieira et al. 2020). These networked solutions provide targets for cyberattacks that would be more difficult to carry out with separate systems; however, the high level of monitoring by sensors etc. also makes attacks and incidents easier to detect.

It is assumed that the digital networking of critical infrastructure will continue to increase (Caradot et al. 2023), for example in the context of smart city applications. For example, the networking of the electricity grid and meters can enable more efficient control of energy consumption (Dupree n.d.) and the sustainability of public infrastructure and services of general interest can be improved through the networking and integration of urban infrastructure (Mühlichen 2020). The resulting increased exchange of information inevitably entails increasing risks for the cybersecurity of public infrastructure and data protection. In particular, the networked structures of smart cities not only increase the probability and potential intensity of harmful cascading effects, but also mean that security breaches in one operator's network automatically pose a threat to other operators (Kalinin et al. 2021; Caradot et al. 2023).

In the future, there will therefore be changing and more stringent demands on cybersecurity, which will not only require increased vigilance against threats to local critical infrastructure, but also against regional and global systems such as submarine data cable networks, energy supply pipelines and offshore energy installations, the respective transfer and transport routes and the corresponding landing and distribution stations (Pawlak 2023).

One core concept here is the resilience of IT systems. While resistance is about fending off attacks completely, resilience is about minimising the damage caused by an attack. The concept of IT resilience follows the “Assume Breach” approach, which postulates that it is not a question of if, but when, a cyberattack will be successful (Herpig 2023). The increasing digitalisation and networking of critical infrastructure, combined with ever more sophisticated attack possibilities, means that cybersecurity must increasingly focus on resilience (Demmig 2020; Mühlichen 2020). One possible goal could be to minimise the possible consequences of a failure of individual system components by setting up redundant structures (Pawlak 2023; p. 161).

The example of a cyberattack on Deutsche Windtechnik in April 2022 (Deutsche Windtechnik AG 2022) shows how the resilience of critical renewable energy infrastructure can already be ensured during the planning and construction of physical-digital systems. This can minimise the impact of attacks aimed at temporarily or permanently disabling these systems (Pawlak 2023). Although the attack meant that communication to 2,000 wind turbines in the North Sea had to be shut down for two days, the attack did not cause any significant damage (Deutsche Windtechnik AG 2022). On the one hand, this was made possible by the decentralised nature of the IT system of the support company, which meant that the attack could be countered almost in isolation. On the other hand, the configuration of the wind turbines allowed them to continue operating autonomously even if communication was lost, which meant that the continuous supply of energy could be maintained (Pawlak 2023).

The “Directive on the resilience of critical facilities” has been in force in the EU since 2022 (European Parliament and Council of the European Union 2022). The German government’s National Security Strategy, adopted in 2023, defined the protection of critical infrastructure and the strengthening of cybersecurity by the state, business, science and society as important components (Federal Government 2023f). To enshrine the special protection of critical infrastructure in law, the Federal Ministry of the Interior is also planning to pass the so-called Kritis Umbrella Act in 2024. This intends to create a uniform level of protection for the relevant infrastructures, which is currently still very inconsistent due to the large number of state, municipal and private operators (Kleine and Barthel 2023).

2. Attacks on companies and value chains

Germany is one of the countries most affected by cyberattacks worldwide. In 2020, the economic damage caused by cybercrime already amounted to 1.6% of GDP (Hauff and Reller 2020). The threat situation in cyberspace, which had already been tense for years, has intensified significantly since 2020, partly because the Covid-19 pandemic has led to rapid and erratic digitalisation in various areas of work. This has created new gateways for cyberattacks (Dreißigacker et al.; Möller 2023).

The Covid-19 pandemic and its digitalisation push have also created new dependencies on information technology, the failure of which can threaten the existence of organisations and companies. At the same time, there are still knowledge gaps and uncertainties, especially among SMEs, about how they can arm themselves against digital threats (Petretto and Heckler 2021). Although the threats posed by cyberattacks are becoming increasingly diverse, ransomware attacks are still one of the biggest threats to companies’ IT security and have a lasting impact on entire value chains (Federal Office for Information Security (BSI) 2023b). In addition, there are new methods such as social engineering, which specifically targets human vulnerabilities and uses various forms of manipulation, e.g. to get employees to disclose sensitive or secret information about their company (Ardagna et al. 2022).

Inadequate cybersecurity and insufficient awareness among companies of the risks of cyberattacks are also problematic in view of the fact that the digital age is

opening up new gateways and opportunities for industrial espionage. According to the BMI (BMI n.d.), foreign intelligence services try to obtain information about new technologies and research results in order to save their own economy the costs of research and development. In addition to the use of traditional means and methods of espionage, increasing electronic networking has led to new and increased risks in cyberspace. Internal and external security risks in the real and cyber world therefore require holistic economic protection that also takes into account the dangers of industrial espionage.

Cyberattacks on companies and value chains are also dangerous from an environmental perspective. On the one hand, they can trigger incidents with potentially serious environmental consequences, such as fires, explosions and the release of hazardous substances (see Emerging Issue 1; Iaiani et al. 2021). Secondly, cyberattacks cause high costs – both in the form of damage caused and in the form of investments in cybersecurity that companies have to make as part of their security measures. Between September 2023 and September 2024, German companies suffered economic losses of EUR 178.6 billion as a result of cyberattacks, which is EUR 30 billion more than in the previous year (Bitkom e.V. 2024). As many cyberattacks and the associated damage to companies are not reported to the BSI for a variety of reasons, Demary (2022) assumes a high additional number of unreported cases. In order to achieve climate neutrality by the middle of the century, KfW estimates that the private corporate sector will need to invest around EUR 120 billion per year (KfW Research 2023; see chapter 2.7). On average, cyberattacks therefore cost companies almost twice as much as they would have to invest to achieve climate neutrality. Cyberattacks therefore not only hinder the technological side of the sustainability transformation by causing economic damage to companies through cyber espionage and the disruption of production chains, but also act as a barrier to investment. The high costs of cybersecurity and resilience are a burden on companies and prevent investments that could otherwise be channelled into sustainability and environmental protection.

3. Attacks on political institutions

Cyberattacks on German state institutions have increased in intensity in recent years. These attacks originate from both state and private actors and pursue various motives.

Government institutions, as well as companies and private individuals, are increasingly confronted with attacks with blackmail intent, e.g. through the use of ransomware (Möller 2023). In 2021, a German municipality declared a state of emergency for the first time due to a cyberattack. The district of Anhalt-Bitterfeld was paralysed by a ransomware attack to such an extent that, the payment of social and maintenance benefits was temporarily no longer possible (Heinrich Böll Foundation 2023). This attack on the district was not primarily designed to cause damage to the administrative apparatus of the municipality, but to extort a ransom to release captured data.

The Federal Office for the Protection of the Constitution (BfV) also warns of targeted cyberattacks by foreign intelligence services on German politics. Targeted cyberattacks are also used in the context of hybrid campaigns by foreign intelligence services, in which various measures are orchestrated to destabilise a target country (Möller 2023). State actors can usually draw on a wealth of resources to carry out complex cyberattacks using sophisticated methods, such as espionage attacks (Möller 2023). Such attacks on political institutions can contribute to undermining society's trust in the state and government. Studies indicate that even the perception that a critical service could be curtailed by a cyberattack can lead to uncertainty and unrest among the population (Shandler and Gomez 2023).

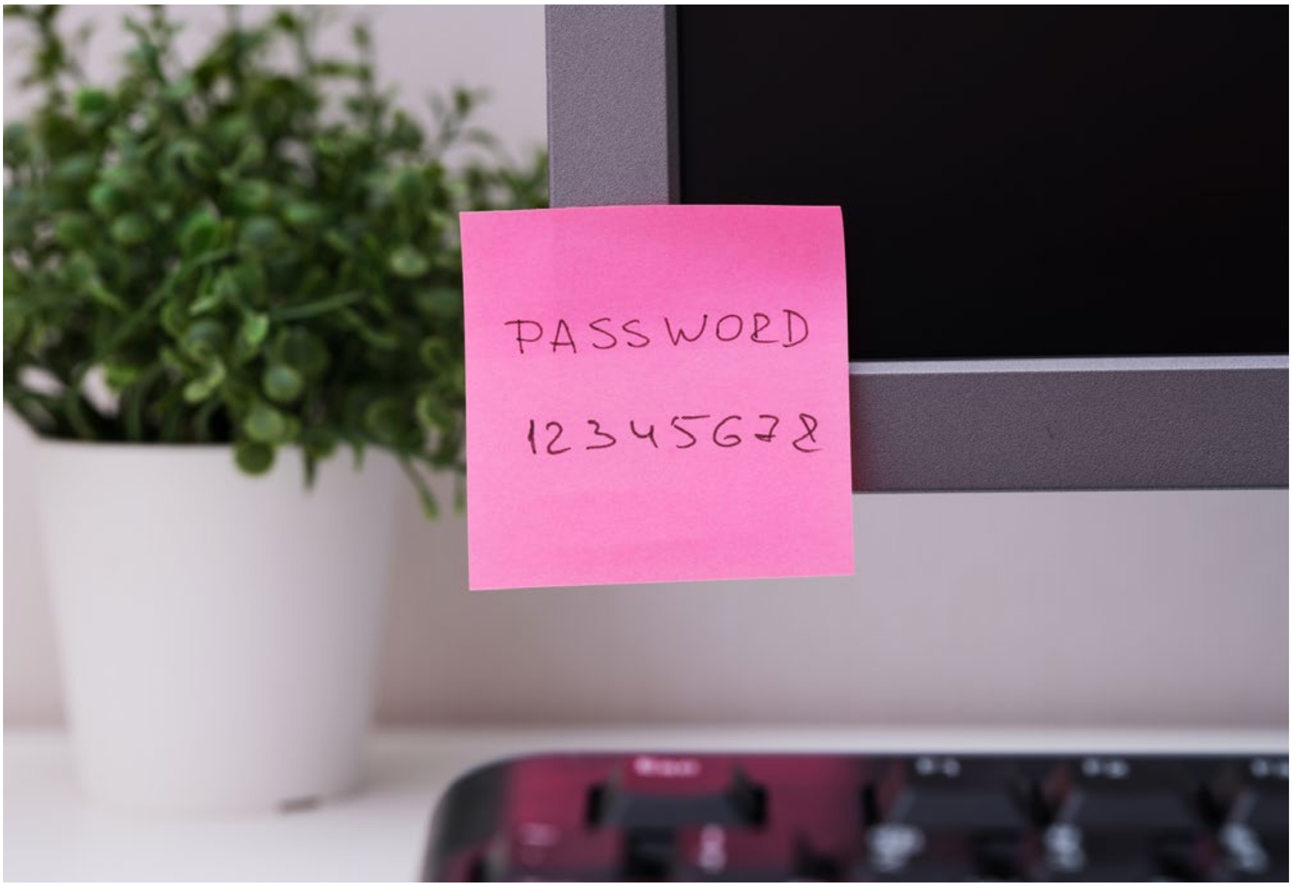
From an environmental perspective, attacks on political institutions are a practical problem: they can have negative consequences for state or municipal environmental administrations and thus hinder the implementation of nature conservation measures, for example. In the case of the attack on the IT of the district of Anhalt-Bitterfeld, it became known more than a year after the attack that the district had permanently lost access to one of the largest environmental databases in Germany, in which measurement data on thousands of suspected contaminated sites in a former GDR chemical complex was stored (Roth 2023). The cyberattack has made significant information on environmental pollution inaccessible, which will have to be compiled again, posing significant challenges for local environmental management and costing millions of euros (Roth 2023).

Another example shows how cyberattacks can be used in a targeted manner to erode trust in public institutions and in science, thereby undermining social acceptance of climate and environmental protection measures. In 2009, as part of a cyberattack on a climate research institute at a university in the UK, masses of documents and confidential emails were stolen and selectively published on the internet to create the impression of fraud. The data theft, known as "Climategate", was a sophisticated and carefully coordinated attack and took place shortly before the UN Climate Change Conference in Copenhagen in order to discredit scientific findings on climate change and their authors (Schnabel 2009; Leiserowitz et al. 2013; McKie n.d.). According to media reports, this has massively damaged public policy making in the United Kingdom and other Western countries and has also led to an increase in Western media coverage of those arguments that deny climate change (Schnabel 2009; McKie n.d.). In the USA, Climategate led to a measurable decline in society's overall belief in climate change, risk perception and trust in science (Leiserowitz et al. 2013). The cyberattack on the research institute therefore had a significant impact on public perception of global climate change and trust in science.

Attacks like this could also affect government agencies such as environmental authorities and cause considerable damage to society: According to Shandler and Gomez (2023) cyberattacks targeting public institutions or public service structures tend to reduce the population's trust in the state. The cybersecurity of political institutions is therefore essential not only from an environmental perspective, but also from a fundamental democratic perspective, and measures to increase the resilience of IT systems are necessary to prevent cyberattacks from destabilising political systems and ultimately society.

4. Attacks on the formation of opinion

The massive wave of misinformation and conspiracy theories spread online during the Covid-19 pandemic has shown that, in the digital age, times of crisis and uncertainty are deliberately exploited to spread uncertainty among the population, drive social division and undermine trust in government measures. Since 2020, there has been a sharp decline in the German population's trust in democracy. At the same time, more and more citizens doubt that the state is capable of fulfilling its tasks and solving problems (see chapter 2.6). Digital attacks on opinion-forming and social discourse are often targeted at politically ac-10tive individuals, but also include targeted disinformation on certain topics. Some of the attack patterns and strategies used have been established for a long time, but are gaining momentum and reach on the internet thanks to technical innovations in the digital world (see chapter 2.8), which are opening up new possibilities.



Attacks on private individuals and public officials are currently gaining a new dimension, particularly through so-called deepfakes. These are image, sound or video recordings that can be manipulated at will using artificial intelligence in order to depict people in negative contexts or attribute statements to them that could undermine their political or social standing (Doss et al. 2023). For example, climate activist Greta Thunberg's call for the use of "vegan grenades" in armed conflicts was used to ridicule her commitment to the environment through exaggeration. Although the video in question was originally created for satirical purposes, the corresponding reference was sometimes deliberately removed when it was disseminated on social networks (Bart 2023). Advances in the field of AI suggest that such images and videos will become increasingly easy to produce in the future and at the same time increasingly difficult to distinguish from real images. As early as 2023, 27 to 50% of respondents in a study were unable to distinguish between authentic videos and deepfakes (Doss et al. 2023). This percentage could rise even further in the future.

In addition to individuals, entire subject areas are also repeatedly the focus of disinformation campaigns. In the scientific context, a distinction is made between science denialism (e.g. denial of climate change, the Holocaust or the usefulness of vaccines) and pseudo-theories, such as homeopathy or creationism; both of these variants of pseudoscience are harmful to society and/or the environment (Hirvonen and Karisto 2022). It is known that political opponents of climate protection measures, such as autocratic regimes or supporters of anti-democratic movements (see chapter 2.4), undermine public trust in scientific expertise, hinder political decision-making processes and sabotage the implementation of effective solutions to the climate crisis (Calliess 2021; Berger 2022). According to the IPCC, disinformation has already helped to delay urgent action on climate change in the past (Freiling and Matthes 2023).

In the digital world, such disinformation is spreading rapidly, and the information described in Chapter 2.8 offer many indications that existing problems could become even more acute. For example, pseudoscientific articles aimed at undermining climate protection measures can be produced in large numbers and with little effort using AI applications and published in predatory journals in return for payment and without the review process customarily required by academic publications (Krawczyk and Kulczycki 2021). This provides opponents of such measures with a supposed scientific foundation in social and political debates. Even outside the scientific context, AI-generated "evidence" of disinformation is becoming increasingly difficult to identify and requires ever greater effort to refute. In social media, misinformation on climate change is shared more frequently than verified, scientifically sound content, and thus reaches a wider audience (King et al. 2022).

Both the type of misinformation disseminated and the strategies used to spread it are constantly changing. In the past, for example, climate change was often openly denied. Over time, this has shifted to different, at first glance less confrontational strategies. For example, claims that describe climate change mitigation and adaptation measures as a threat to the economy or national security or attribute positive consequences to climate change, such as higher crop yields of certain plants, are becoming increasingly popular (Berger 2022; Berger et al. 2023). The complexity of the challenges posed by climate change is deliberately used to sow doubt about the need for climate protection measures or to discredit research findings (Berger et al. 2023). This is referred to as "deny, delay and diffuse" tactics, which aim to prevent political measures and regulations on climate change by influencing public opinion (Berger et al. 2023) by casting doubt on the scientific evidence base, delaying political action and diverting social discourse to other issues (King et al. 2022). Common arguments for these tactics include whataboutism ("Why should we take action on climate change when country X produces far more emissions?") or doomerism: "All action is too late, climate change is unstoppable" (Lamb et al. 2020).

Digital attacks on opinion-forming are coordinated and targeted. The perpetrators and multipliers of such attacks can be other states and intelligence services, but also individuals from within Germany who are pursuing opposing political goals (see chapter 2.4). In democratic systems, the implementation of environmental policy goals such as transformation, climate protection and nature conservation is linked to support in society, which is to be reduced in this way. Effective environmental protection therefore increasingly also means being able to counter these attacks appropriately through prevention and resilience.

Politicians and civil society are already tackling the problem with a variety of projects and prevention programmes. Since 2022, for example, the BMBF has been funding a series of research projects that focus on recognising, understanding and combating fake news (Federal Ministry of Education and Research (BMBF) 2022). The European Commission is also funding a large number of projects to combat disinformation (European Commission (EC) n.d.) and the Bertelsmann Stiftung has been running the participatory project "Forum against Fakes – Together for a Strong Democracy" since January 2024[44], in which recommendations for dealing with disinformation are to be developed for politicians together with citizens (Bertelsmann Stiftung 2024).

Conclusion for environmental policy and research

The increasing networking of all areas of life means that cyberattacks are also possible (and more likely) in a wide variety of forms, making cybersecurity an increasingly relevant concept whose approaches must be selected appropriately depending on the application.

Attacks on political institutions and the targeted influencing of opinion formation have a direct impact on trust in the state and its environmental protection measures. Cyberattacks not only cause physical damage, but also undermine social trust in the government. Targeted disinformation is particularly critical in the context of environmental protection issues. Examples such as Climategate show how cyberattacks can be used to increase social division and undermine trust in scientific findings on climate change. In this context, greater awareness within society and institutions is required in order to minimise the impact of attacks on political institutions and opinion-forming and to protect against them as comprehensively as possible.

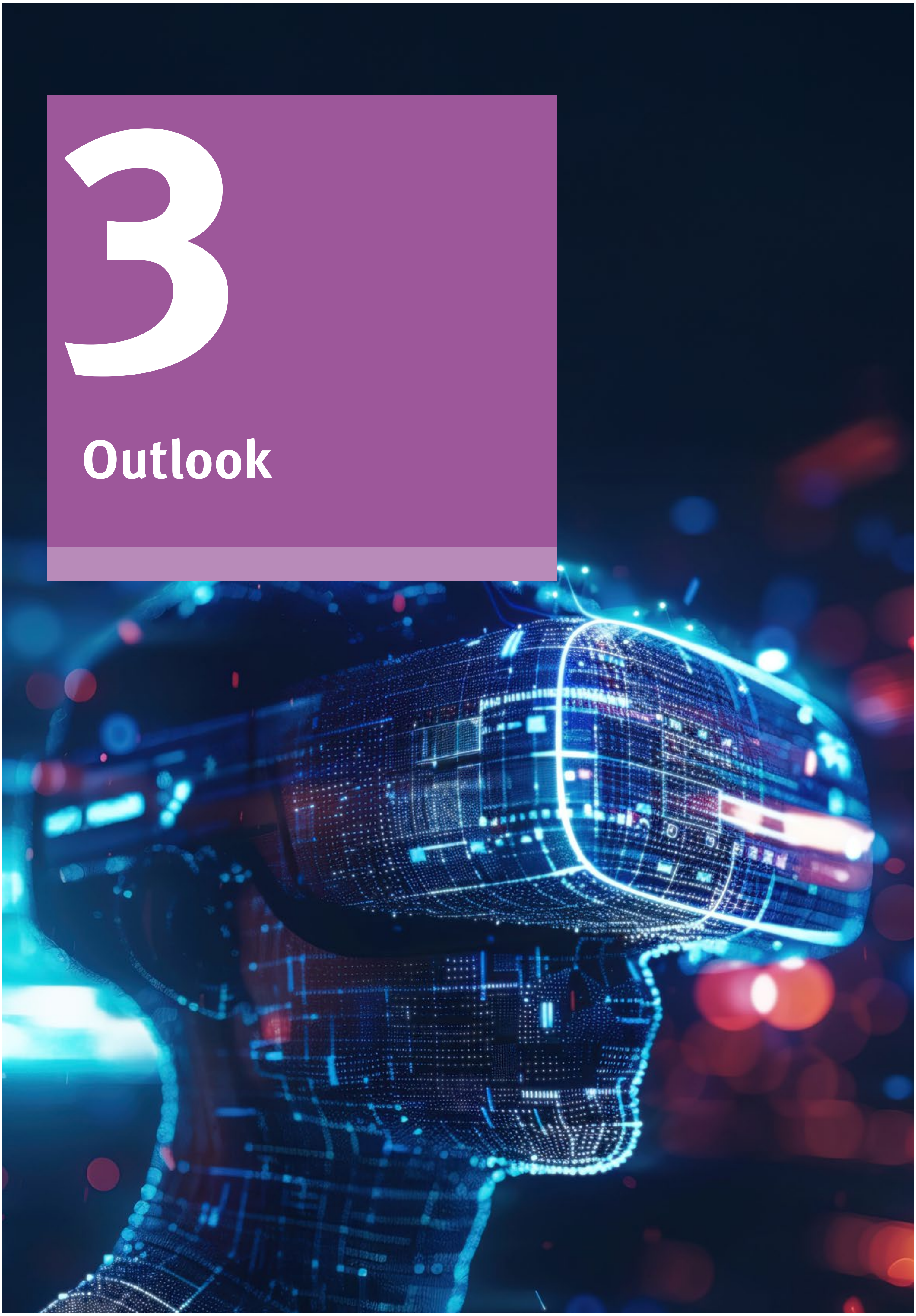
The interaction between cyberattacks and environmental aspects requires the integration of both issues in future political strategies in order to prevent environmental damage, maintain the ability of environmental administrations to work, restore and strength-

44 https://forum-gegen-fakes.de/

en trust in state institutions and promote social acceptance of environmental protection measures. Successfully integrating cybersecurity and environmental protection means not only protecting the integrity of data and technologies, but also ensuring that the impact of cyberattacks on the environment is limited (Sühlmann-Faul and Rammler 2022). Conversely, attention must also be paid to how climate change and a changing natural environment threaten cybersecurity, for example when extreme weather events damage critical infrastructure and cybercriminals exploit emerging vulnerabilities (Arntz 2020).

As all of the attack patterns described are likely to increase in the future due to further networking, resilience is becoming an increasingly important approach to dealing with cyberattacks in order to minimise the negative consequences in the event of an attack. The spectrum of possible measures ranges from maintaining redundant infrastructure to prevent outages (see Emerging Issue 1) and improved regulation of online platforms and their moderation of disinformation to awareness-raising and media literacy. Most of these approaches only indirectly affect the environmental sector; however, the role of the Environment Department could be to further develop the environmental dimension of cyberattacks in interdepartmental cooperation. On the other hand, it could promote the dissemination of environmental issues and scientifically sound content through comprehensive public relations work.

3 Outlook



3 Outlook

This report presents nine selected future topics from the third horizon scanning cycle, which was launched in 2022. These were identified as key trends with potential environmental impacts and corresponding points of contact for the Environment Department.

The process was shaped by the aftermath of the Covid-19 pandemic and Russia's war of aggression against Ukraine. While the links to environmental policy are immediately apparent in some of the nine wide-ranging future topics, such as "desalination", the links to environmental policy are only apparent at second glance in other trends examined, such as "cybersecurity" or social trends, such as "democracy in danger".

The future topics identified can be assigned to the overarching topics of the strategic foresight in the Environment Department (see Figure 13). The subject areas represent those areas in which the Environment Department would like to identify new developments that are relevant to its own work in the future. In the horizon scanning process, they served as search areas in which weak signals were scanned for (see Chapter 1.2).

Environmental policy links to future topics

For the Environment Department, the early identification of new topics, trends and emerging changes is an important part of a forward-looking and design-oriented environmental policy. This strengthens the Department's strategic ability to act in order to respond proactively to future threats to people and the environment and to make better use of opportunities to improve the state of the environment. Horizon scanning fulfils an important function for the Environment Department by

- recognising and describing new socio-economic and technological developments at an early stage,
- making the often still vague topics and developments plausible, structured and thus accessible for further processing and implementation,
- assessing the nature and extent of their impact on humans and the environment,
- formulating initial indications of the urgency and relevance of the topics in political prioritisation.

The nine future issues presented in the report have not yet found their way into environmental policy action, at least not in the form presented here. The analysis of the environmental impacts of the individual future topics has provided numerous indications of where there are environmental policy points of contact that can be taken up and considered further in the context of environmental research and policy. Initial starting points are presented below, based on the respective topic-specific conclusions:

- Lab-grown future: The lab-grown future encompasses more than just in vitro meat. More and more food (e.g. fish, eggs, milk) and materials (e.g. leather, wood, cotton) are being produced in laboratories in cell factories, as are chemicals, energy and fuels. If optimally implemented, lab-grown future production processes can contribute to a reduction in greenhouse gas emissions, land and water consumption and animal suffering, as the production of food and materials is shifted from conventional agriculture to a controlled laboratory environment. At the same time, the high-tech production processes cause new problems for the environment, particularly in terms of their energy and resource consumption. A complete substitution of conventional production is not to be expected in view of the high production costs; rather, selective substitution could have a positive environmental impact. In order to make the lab-grown future sustainable, comprehensive environmental assessments over the entire life cycle of the new products are necessary. Rebound effects must be avoided and the lab-grown future must be embedded in a holistic sustainability strategy that emphasises sufficiency and the reduction of consumption.

- The future of seawater desalination: Freshwater scarcity is already a pressing issue in many places around the world. Due to the almost inexhaustible resource of seawater, seawater desalination offers great potential for counteracting freshwater scarcity. Seawater desalination has various effects on the environment. Firstly, the energy requirement is very high, which is currently mostly covered by fossil fuels and leads to high CO_2 emissions. Secondly, highly concentrated brines are produced, which often contain additional chemicals and heavy metals. Their discharge into the sea endangers ecosystems through oxygen depletion and pollutant enrichment. Thirdly, water extraction and discharge can affect marine life. In addition, resources are consumed in the production of the plants. This gives rise to a number of starting points for environmental policy. The decarbonisation of desalination plants through the use of renewable energies is essential, the disposal of brine should be strictly regulated and, at the same time, research into innovative processes for brine utilisation should be promoted. In addition, the impact on marine ecosystems must be minimised and seawater desalination must be integrated into a sustainable water management system that prioritises water conservation and alternative water sources.

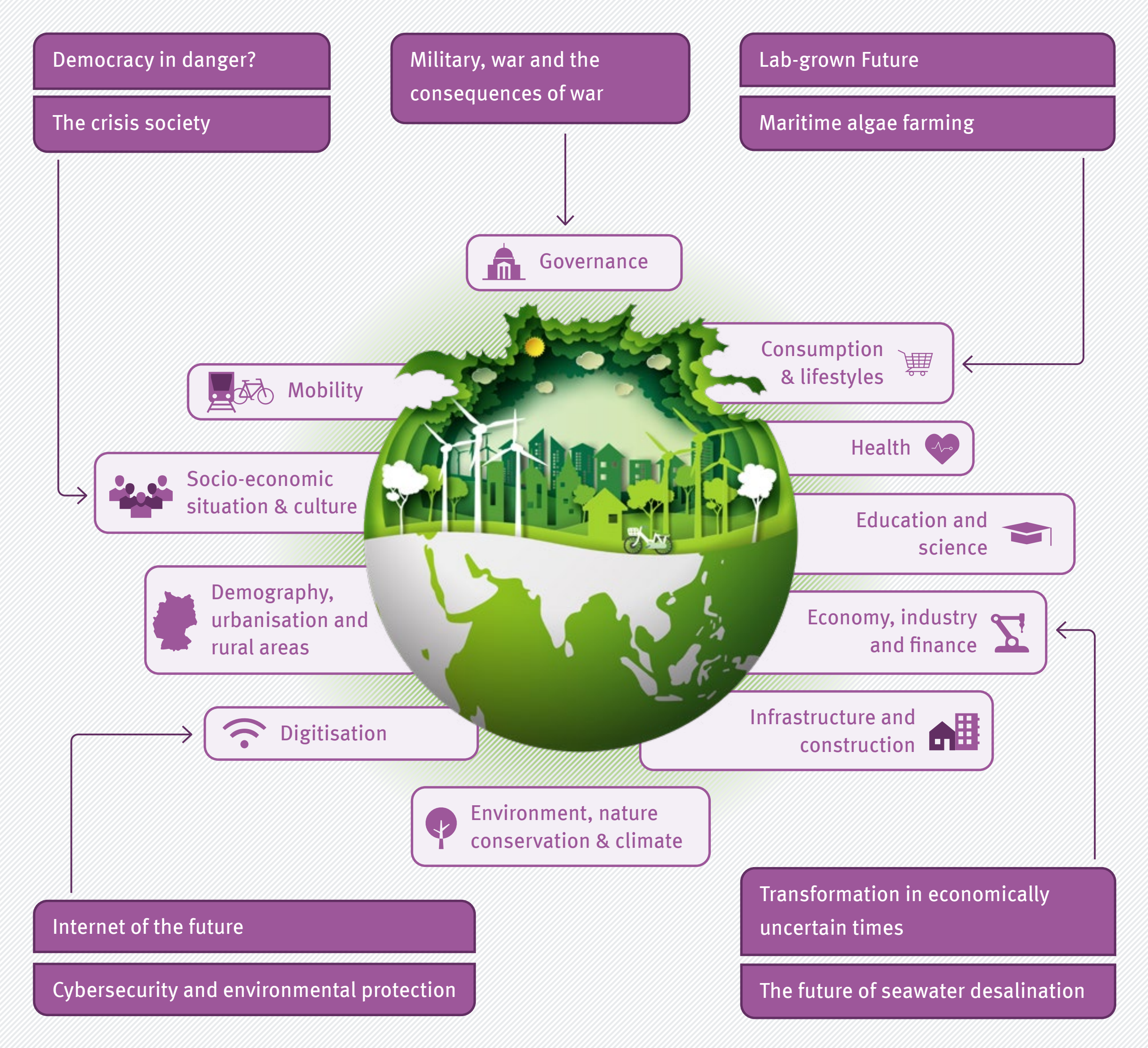
- Maritime algae farming: Algae have existed on earth for billions of years and have been used by humans for a long time. Recently, however, new potential uses have opened up for macroalgae, which can serve as a sustainable source of food, raw materials and products for the healthcare sector. Algae farms offer great potential for environmental and climate protection: they can bind CO_2, improve water quality, contribute to coastal protection and reduce pressure on terrestrial ecosystems by replacing agricultural products. However, they also harbour risks for marine ecosystems. For example, algae farms can endanger natural algae stocks, have a negative impact on biodiversity and cause negative environmental impacts due to the high energy requirements for further processing, e.g. drying. The Environment Department could support and help shape the development of new algae farming from the outset. Modelling ecological effects in advance and continuous monitoring during the operation of algae farms could help to minimise negative impacts on marine ecosystems. As marine algae production interacts with existing agricultural structures, a cross-departmental strategy is a good way of exploiting potential synergies and avoiding rebound effects. The Environment Department could also inform consumers about the potential of sustainable algae farming and help shape demand through public procurement.

- Democracy in danger? Anti-democratic forces are gaining influence worldwide and endangering democratic systems, with negative effects on environmental and climate policy. Anti-democratic tendencies and the spread of disinformation, especially in the context of climate change, undermine trust in democratic processes and scientific knowledge. They make international cooperation more difficult and hinder the implementation of environmental and climate protection measures. The rise of populist parties in Germany jeopardises progress in environmental policy and could slow down environmental initiatives. The Environment Department can make an important contribution to strengthening democracy and environmental protection. International cooperation can improve the transparency of environmental responsibilities. At national level, the Environment Department should counteract disinformation by stepping up communication measures on environmental and climate protection and on the consequences of anti-democratic developments. The promotion of information campaigns and fact-checking services as well as the strengthening of citizen participation models can strengthen the democratic basis of environmental protection.

- Military, war and the consequences of war: Wars and military conflicts have a devastating impact on the environment and nature, both during combat and in the post-war period. Environmental destruction is used as a war strategy, for example through the use of environmentally disruptive technologies or the targeted destruction of critical infrastructure. The increasing mechanisation of the military also leads to high resource consumption and CO_2 emissions. The Environment Department can work towards better protection of the environment in war and post-war situations by advocating the closure of regulatory gaps in international agreements and the development of sanction mechanisms for violations. It is also important to promote research into the environmental consequences of war and sustainable military technologies. The Environment Department can support cooperation with NGOs and civil society organisations and advocate an interdepartmental strategy to strengthen the resilience of climate and environmental policy.

Figure 13

Allocation of future topics to the subject areas of the strategic foresight of the Environment Department



Source: own presentation

- The crisis society: German society is in a phase of polycrisis, which is leading to stress, exhaustion and a loss of trust in political institutions. Many people feel insecure and overwhelmed in the face of crises such as climate change, war, pandemics and inflation. The reactions to the polycrisis are diverse: some people react with crisis resignation and denial, withdraw into their private lives and turn away from social and political issues. Others are becoming increasingly involved in protest movements, such as Fridays for Future or the Last Generation, to draw attention to the urgency of the crises. Stress and sickness-related absences are also increasing in the world of work, which can affect productivity and the implementation of the sustainability transformation. By communicating transparently, promoting citizen participation (e.g. citizen dialogues, participatory budgeting) and building trust in the system (e.g. through consistent environmental policy and communicating success), the Environment Department can help to reduce fears and boost confidence. Constructive dialogue with protest movements such as Fridays for Future and taking their concerns into account are also important in order to reduce frustration and polarisation. The Environment Department can also promote resilient working models that improve productivity and well-being in the world of work, e.g. by promoting working from home and flexible working hours.

- Transformation in economically uncertain times: The German economy is facing the challenge of transformation towards a socio-ecological market economy, but this is complicated by economic uncertainties, high investment requirements and the question of a fair distribution of transformation costs. Falling incomes and wealth among citizens can impair acceptance of the socio-ecological transformation and the ability to invest in private climate protection measures. Companies are under economic pressure and must invest in climate protection and innovation despite uncertainties. The state is faced with a shrinking national budget, which limits the state's ability to invest in the transformation. The Environment Department can make an important contribution to shaping the transformation in a socially responsible way by taking into account the distributional effects of environmental policy instruments and creating compensation mechanisms. The promotion of SMEs and the energy-efficient refurbishment of rented housing are examples of targeted measures. The Environment Department should actively participate in the distribution policy discourse and emphasise the economic importance of environmental policy. The further development of export promotion programmes for environmental technologies and the establishment of a network of supporters in the economy can also drive the transformation forward.

- Internet of the future: Innovations such as 5G, edge computing, extended reality and artificial intelligence (AI) are making the internet of the future increasingly immersive and blending physical and virtual worlds. New end devices such as VR/AR glasses, haptic suits and AI-supported applications enable a new user experience. The production and operation of the new hardware consume considerable resources and energy and contribute to the generation of electronic waste. The new data-intensive content and applications increase data traffic and thus the energy requirements of the network infrastructure. At the same time, the internet of the future also offers opportunities for environmental education and the communication of environmental issues, e.g. through immersive nature experiences or the visualisation of climate change impacts. The Environment Department should establish detailed monitoring of the environmental impact of the internet of the future in order to better assess opportunities and risks. Important environmental policy starting points are the promotion of energy and resource-efficient hardware, the promotion of repair options and recycling methods as well as the use of renewable energies for the operation of the technologies. The Environment Department should also work together with other departments to promote the sustainable design of the Internet of the future.

- Cybersecurity and environmental protection: Cyberattacks are on the rise and threaten critical infrastructures, companies, political institutions and the formation of public opinion. Increasing networking and digitalisation are increasing the attack surface and opening up new opportunities for cybercriminals. Cyberattacks can have a significant impact on the environment. Attacks on critical infrastructure such as power plants or sewage treatment plants can lead to accidents and release pollutants. Cyberattacks on companies can disrupt the production of environmental technologies and hinder investment in climate protection, and attacks on political institutions and the spread of disinformation can undermine trust in environmental policy and science (e.g. "Climategate"). The Environment Department should strengthen the cybersecurity of critical infrastructure in the environmental sector and advocate better regulation of online platforms in order to curb the spread of disinformation. It is also important to raise public awareness of the risks of cyberattacks and promote media literacy. The development of a dedicated cybersecurity strategy by and for the Environment Department can also be a measure to increase the resilience of the Environment Department against cyberattacks. In addition, the Environment Department can work together across departments to integrate environmental and cybersecurity aspects.

Cross-references to social dynamics

There are numerous cross-references between the future topics, i.e. the various developments identified in the respective emerging issues influence each other. This can be both a strengthening relationship and a slowing influence. Such cross-references are described in detail in the chapters on the respective emerging issues.

In this horizon scanning report, interactions between the nine future topics presented have already been identified at the level of the trend chapters by means of cross-references to the related chapters. The following section highlights the cross-thematic developments that represent the "major" socio-political dynamics of our time, which affect all identified trends and should be taken into account when shaping the future of these developments.

- Loss of trust in democracies and radicalising societies: A central problem that brings together many of the trends and developments described is the loss of trust in democratic institutions. This is exacerbated by disinformation – including in the context of (a) social networks – which exploits existing insecurities and fears. It is particularly dangerous that disinformation leads to the radicalisation of certain social groups, which are increasingly looking for scapegoats – currently often "the Greens" or "environmental policy", but also "migrants". This radicalisation undermines social consensus and blocks necessary reforms, including in the area of ecological transformation. A targeted strategy that emphasises transparency, dialogue and education is essential in order to strengthen trust in democracy and overcome social divisions.

- Perception of threat and fears in the polycrisis: Progressive climate change and other profound societal changes increase the pressure on individuals and communities. This pressure to change creates fears and insecurities that are exacerbated by the constant experience of crises – be it economic downturns, pandemics or geopolitical conflicts – and can result in a "crisis society". People feel threatened and increasingly react defensively or reject necessary transformations. One example of this is the rejection of (social) sustainable innovations, which are seen as a threat to established structures. To counter these fears, it is crucial to make political measures transparent and actively involve the population in the transformation process in order to defuse perceptions of threat and build trust in politics.

The interactions between rising inequality, loss of trust, disinformation and the experience of the crisis are leading to an increasingly radicalised and fragmented society. This requires a fundamental rethink of the way in which political measures, particularly in the area of environmental and climate policy, are designed and communicated. To this end, a process should be initiated to rethink the communication of environmental policy measures and make use of all possible ideas from a wide range of areas (digitalisation, marketing, psychology and neuroscience, etc.). In this way, environmental research and environmental policy measures can perhaps be communicated in the future in such a way that social fears are accurately allayed, social cohesion is promoted and a positive narrative about our future sustainable future is anchored in society, in which the socio-ecological transformation is actively and jointly shaped.

Next steps

With the completion of the third horizon scanning cycle, the Environment Department has a compact overview of nine emerging and environmentally relevant future topics. The next step is to analyse these results and translate them into strategic environmental policy. This can be done, for example, by discussing the topics in various formats such as workshops, expert discussions or conference contributions. In particular, topics that are at an early stage of development and where there are gaps in knowledge regarding possible environmental impacts can be further processed by the Environment Department as part of in-depth analyses. Methods of strategic foresight, such as trend analysis or scenario development, can be used to develop concrete indications for environmental policy options.

The decision as to whether and how the future topics presented are to be further processed should be made on a topic-specific and cross-departmental basis, and possibly also across departments. It is possible that some topics will not be pursued further, or will be shifted to other responsible departments. The horizon scanning process is also used to make conscious decisions about not working on topics. The world is evolving, and with it many of the topics presented in this report. It is also conceivable that the topics presented will be considered again in future Environment Department horizon scanning cycles, especially if new environmentally relevant aspects become apparent.

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1 Introduction

1.1 Identification and genesis of future topics

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2 Future topics

2.1 Lab-grown Future

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2.4 Democracy in danger?

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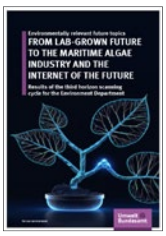

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