Workshop report

Ensuring the environmental sustainability of emerging technologies – 1

International Risk
Governance Center

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Executive summary

On 27–28 October 2021, the EPFL International Risk Governance Center (IRGC) organised an expert workshop to discuss concerns about the environmental sustainability of emerging technologies and the extent to which these concerns are currently considered by those who develop, fund or deploy new technologies. The workshop examined ways to ensure that concerns are addressed at the beginning of the development process through the early identification, assessment and management of possible risks. It then considered the kinds of guidance that could be useful to technology developers, industry leaders, investors, regulators and others, to ensure that outcomes of an emerging technology do not threaten environmental sustainability, or that potential adverse effects are identified and addressed early.

The workshop reviewed various response strategies and formulated some generic recommendations across five distinct technology domains: chemicals and advanced materials, synthetic biology, digital technologies, carbon dioxide removal (CDR) and sequestration, and space technologies.

Emerging technologies

Emerging technologies are new technologies or advancements in existing technologies that dramatically improve their performance. Some can disrupt existing industrial processes or contribute to fundamental economic and societal changes. They can be radically novel, develop fast and have powerful consequences. Emerging technologies pose unique challenges to risk assessors and managers because of a general lack of procedures and tools to assess their potential impact, insufficient data on which to build evidence, and pervasive uncertainty about how the technology will mature and be deployed in the market. These challenges are compounded by ambiguity in emerging technology assessments due to diverging views and interests. This ambiguity manifests as a lack of clarity in the value system that underlies tools like environmental impact assessments or life-cycle assessments, or even in the objectives that employing these tools can help achieve.

The importance of developing technologies for combatting climate change, for environmental protection or remediation and, more broadly, for environmental sustainability has been demonstrated in recent years, with much investment poured into them. This report takes a different perspective and addresses concerns raised by the risk that emerging technologies can cause unexpected damage to the natural environment or the climate in the longer term.

Sustainability of technology

Emerging technologies offer a multitude of benefits but can also have adverse effects on the environment. The balance will depend on how narrowly or widely the net is cast to identify applications and their implications, the time horizon considered, and the technologies' specific characteristics. For example, strong policy incentives and increasing attention from policymakers encourage investment in "green" technologies, and support "sustainable finance" to meet the expectations of governments, investors and the public. However, this may lead to promoting and pursuing certain technologies without appropriate impact assessments or due consideration of the possible undesirable side effects. Such a rush to find solutions to immediate problems may overlook the full extent of the longer-term consequences in the natural environment and climate.

Chemicals: Advanced materials and smart nanomaterials

New chemicals and advanced materials that improve industrial and product performance and efficiency may raise concerns about potential long-term environmental damage if they end up in terrestrial or marine ecosystems. Long-term challenges are associated with uncertainty about the environmental impacts of advanced materials, such as with so-called smart nanomaterials (active nano-based products and systems whose function changes in response to external stimuli), and concerns exist over the lack of tools to conduct environmental assessments that are appropriate for new developments.

Synthetic biology: Gene editing and gene drives

Synthetic biology, in particular gene editing and gene drives, can significantly benefit public health, agriculture, environmental remediation and biodiversity conservation. However, it can also cause substantial knock-on effects on conservation, including modified genes spreading to non-target populations and food webs affecting broader ecosystems. As a result, it is often contested within the environmental expert communities. Evidence is lacking on the long-term impacts after release in the natural environment, limiting our ability to evaluate the risk-benefit trade-offs, which makes the early governance of deployment challenging.

Digital technologies: Machine learning, cloud computing and blockchain

Digital technology applications can help reduce stress on the environment in specific domains. They also raise concerns, however, about their environmental and climate impacts, such as through their electricity consumption, use of natural resources, mining of rare earth elements, and waste disposal and recycling. Efforts are underway to measure and report on the carbon footprint of specific applications. The balancing of benefits and risks is particularly challenging, considering the many opportunities offered by digital technologies to contribute to the sustainable development goals.

Carbon dioxide removal and sequestration

CDR is being developed to reduce atmospheric CO_2 concentration, thus mitigating climate change. Its deployment through negative emission technologies is necessary to reach the current climate goals, i.e., to neutralise residual greenhouse gas emissions to achieve net-zero. However, a range of uncertainties are associated with the various CDR approaches, whether nature-based, engineered or hybrid. Adverse consequences on biodiversity, ecosystems and human systems are among the risks, and some of the sequestration of the CO_2 in various reservoirs could be reversed. Some potentially important effects have already been identified if the techniques are deployed on a large scale. Because of their apparent necessity and the flurry of investments to address climate change, some technologies may be used and expanded without a full assessment of their second-order impacts on the environment (or the climate itself through the impermanence of the sequestration).

Space technologies

Satellite operators increasingly use outer space to deliver critical services, including earth observation and environmental monitoring. The growing space infrastructure provides an opportunity to improve sustainability on Earth. However, the increasing risk of collision between satellites and orbital debris, as well as adverse consequences of space activities on the atmosphere, could prevent the sustainable use of space in the long term. The deployment of emerging space technologies may exacerbate environmental sustainability risks, such as collision or pollution.

Matters of concern – Key themes

The report discusses concerns related to several key themes:

- **There are often significant uncertainties involved in the anticipation of an emerging technology outcome**. Thus, instead of passing an overall judgement on a technology, it is necessary to look at the expected outcome of its applications on a case-by-case basis. The outcome of a specific technology may change between the time it appears as an idea and the time it is used in a product, manufactured and placed on the market, i.e., between design and deployment. Moreover, value systems and visions of what is desirable evolve over time, affecting risk perceptions and technology assessments. In the face of promising (but uncertain) applications and potential risks, balancing their benefits and costs, or innovation and precaution, is not a simple technical exercise, but one that requires engaging with various stakeholders who may have different perspectives on the technology and its possible functions and outcomes.

- **Instruments to assess sustainability, which is context- and sometimes case-specific, are lacking**. Although the concept of sustainability is theoretically well defined, translating it into actionable assessment tools and metrics is far from obvious. It is not easy to design criteria, indicators or processes for materialising the concept in the physical world. Moreover, the concept does not apply well to individual products, and requires a systems approach to incorporate the benefits and risks to various actors and systems across the supply chain. Environmental sustainability is a multidimensional concept that requires its potential trade-offs to be addressed transparently. This makes the establishment of actionable tools and metrics challenging.
- **Solutions to immediate problems may not be sustainable in the long term**. In a rush to embrace solutions to deal with well-identified problems, risks to long-term environmental sustainability could be created and neglected. Although response strategies to pressing issues must be developed, rushing to solutions without a sufficient ex-ante evaluation of their potential risks and related uncertainties would be a mistake. In some cases, the cure may be worse than the disease.
- **Temporal issues and biases complicate matters**. Environmental effects may not be visible immediately, and no consensual system exists for internalising the negative externalities that would only manifest in the long term. History and scholars have shown that it is hard to learn from the past and that a range of cognitive and organisational biases explain why humans and organisations are not good at preventing something terrible from happening in the future.
- **The conventional containment approach to risk management has limitations**. Developing ways to prevent a risk's materialisation and reduce its consequences remains effective in several technology domains but becomes challenging with technologies that produce active systems that adapt and change in response to external stimuli. The changing nature of many new technologies that diffuse and alter with use suggests that traditional assessment and management approaches have reached their limits.
- **Society may not agree on what presents a risk to environmental sustainability**. Yet, people's engagement is important to arbitrate trade-offs. Public acceptance and support for emerging technologies can be affected when the potential and actual adverse impacts of the technologies seem to be ignored or downplayed.
- **Regulation faces a pacing problem**. It is hard for regulators to keep pace with innovation and accompany the deployment of new technologies with appropriate regulations.
- **Research priorities are not always guided by moral and ethical considerations**, which are reflected in attitudes towards environmental sustainability. In the absence of such considerations, the default approach becomes that if something can be developed, someone will do it.

Recommendations

Acknowledging the difficulty of capturing and making the concept of environmental sustainability concrete, and taking into account the features of emerging technologies in various fields, this report provides some overarching recommendations:

- **Systematise early-stage technology assessments**, especially in institutions that advise policymakers on where and how to support or regulate specific technologies. Sustainability should not be prescribed or considered only after the technology has been deployed in actual products.
- **Develop methods and tools for prospective life-cycle assessments** to be applied in the early development phases of a technology, when there is a lack of data and uncertainty about the future product and market, but there is still time to change the technology's design to establish

fundamental conditions that would ensure the sustainability of the outcome.

- **Refine the concept of sustainability-by-design**, and develop frameworks and criteria in selected technology domains that funding agencies, investors, industry leaders and regulators could consider to encourage built-in sustainability. Criteria could include safety, resource use and circularity (recyclability), and the effects on greenhouse gas emissions and ecosystems.
- **Create a value proposition for sustainability** that identifies clear, measurable and demonstrable benefits for innovators and investors. A strong value proposition would help innovators reconcile long-term sustainability and short-term innovation goals, and end-users prioritise environmental sustainability in their choices. Government interventions that help internalise both positive and negative externalities associated with sustainability can enhance the value proposition. Performance-based standards and certification also have a role to play in enhancing the business models for sustainability.
- **Work to develop flexible and adaptable regulatory frameworks** that integrate new knowledge generated over time, and consider the possible roles of liability regimes and the judicial system to establish the importance of environmental sustainability in practice, as well as reporting and standards as precursors or proxies of regulation.
- **Establish specific guidelines**, perhaps in the form of a compass (akin to a GPS and map), to indicate the direction to environmental sustainability. The compass would help technology developers, investors, policymakers and others to develop a mindset or appropriate attitude towards environmental sustainability. It would point to approaches for sustainability assessments, policy and legal requirements, and to available incentives that reward engaging in practices for environmentally sustainable technology development, deployment and investment. It would thus also indicate where support can be found to reach sustainability goals.

More research and the development of case studies of specific sustainability challenges and how they are addressed in key technology domains will be needed to refine the recommendations.

Table of contents

Table and figures

List of acronyms

CDR	Carbon dioxide removal
CO$_2$	Carbon dioxide
DACCS	Direct air carbon capture and storage
ECHA	European Chemicals Agency
EEA	European Environment Agency
ELD	European Liability Directive
ERA	Environmental risk assessment
ESA	European Space Agency
EV	Electric vehicles
GDO	Gene drive organism
GHG	Greenhouse gases
GPU	Graphics processing unit
ICT	Information and communication technologies
LCA	Life cycle assessment
ML	Machine learning
MRL	Manufacturing readiness level
PAR	Planned adaptive regulation
RRI	Responsible research and innovation
SDG	Sustainable development goal
SNM	Smart nanomaterials
SSbD	Safety and sustainability-by-design
SbD	Sustainability-by-design
SSR	Space Sustainability Rating
TA	Technology assessment
TRL	Technology readiness level

Introduction

On 27–28 October 2021, the EPFL International Risk Governance Center (IRGC) convened an international and interdisciplinary group of experts to discuss concerns about the environmental sustainability of emerging technology applications and the extent to which these concerns are considered during the technology design and development stages, and in guidance from public policy.

Concerns about profound environmental and climate degradation, often indirectly caused by new technologies, require serious attention. Unfortunately, there exist many emerging technologies that could indirectly adversely impact the environment. Risks to the environment may be slow and unexpected, and it could take a long time before they are noticed and before action is taken to control them. It may even simply be too late, as some effects could be irreversible, or vested interests could block the reversal of decisions and investments.

While working to ensure the environmental sustainability of every emerging technology is a desirable goal, the means to reach it are complex for various reasons. First, establishing an overarching judgement about an emerging technology is inappropriate due to the difficulty of anticipating its outcomes. Second, although the concept of sustainability is easily understandable, its wide reach and vagueness hinder the definition of concrete and indisputable criteria, indicators and assessment processes. Third, there is a temporal issue, as effects on the environment are not visible immediately, and adverse consequences may manifest much later after a product or service is in use. This report assumes, however, that something can be done to guide technology developers and others toward producing technology that does not cause indirect and delayed damage to the environment.

Discussions in the workshop explored the extent to which environmental sustainability concerns are taken into account and what can be done in five distinct technology domains: chemicals and advanced materials, synthetic biology, digital technologies, carbon dioxide removal (CDR) and sequestration, and space technologies.

This report describes the current attitude and instruments available or considered to reach the goal of environmental sustainability. Thus, it suggests ways to address ex-ante environmental concerns that might manifest only after the design choices for a technology are already made.

- **Chapter 1** explores the concept of environmental sustainability in the context of emerging technologies.
- **Chapter 2** discusses matters of concern when evaluating environmental sustainability.
- **Chapter 3** briefly describes cross-sectoral aspects in distinct technology domains in which emerging concerns are beginning to raise attention.
- **Chapter 4** outlines various response strategies to support the development of technical instruments and improve governance and regulation.
- **Chapter 5** offers overarching recommendations for considering environmental sustainability early in the technology development process.
- **Appendix 1** includes detailed notes on the five distinct technology domains.

This workshop report was written with a particular audience in mind: knowledge and technology developers in academia and industry, policymakers and advisers, technology promoters, and investors. Recommendations are formulated in a generic manner. More specific recommendations for selected audiences will be developed after in-depth examinations of specific technologies.

How to use this report

We advise readers to use the report (see Figure 1) as a compilation of aspects that IRGC suggests are relevant to those who want to consider environmental sustainability when developing, deploying, incentivising and regulating new technologies. The chapters and sections are thus, to some extent, independent and do not need to be read sequentially.

Readers interested primarily in specific aspects of the emerging technologies considered in this report may wish to start with Appendix 1.

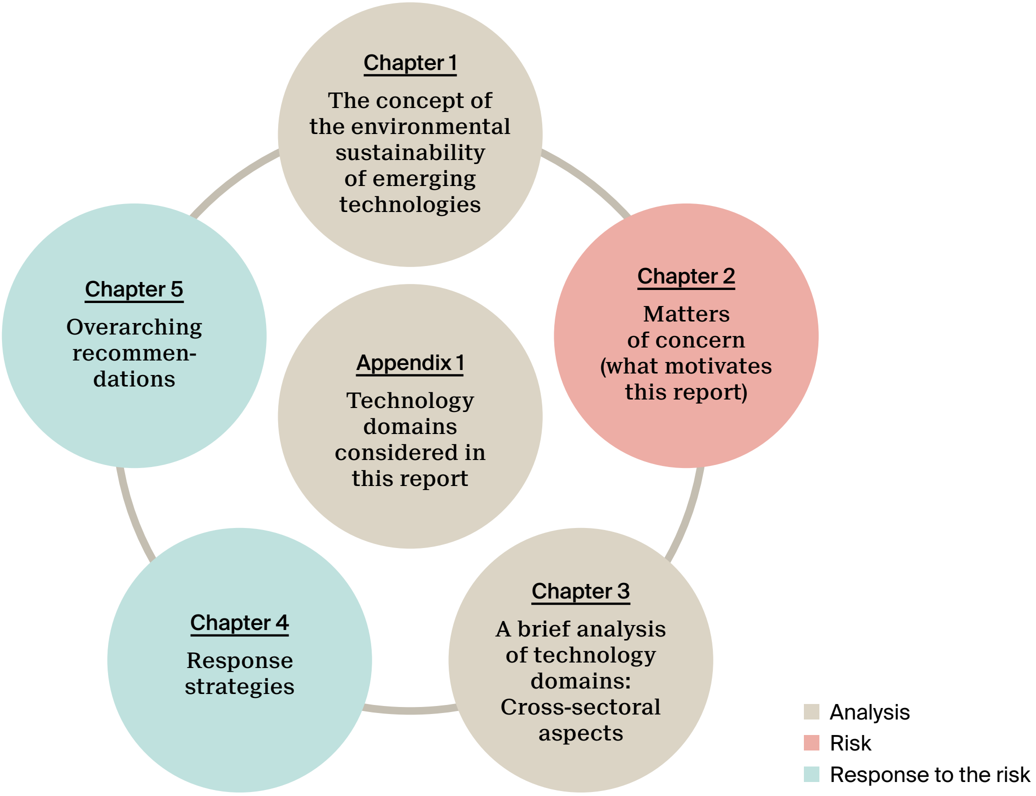

Figure 1 | How to read this report

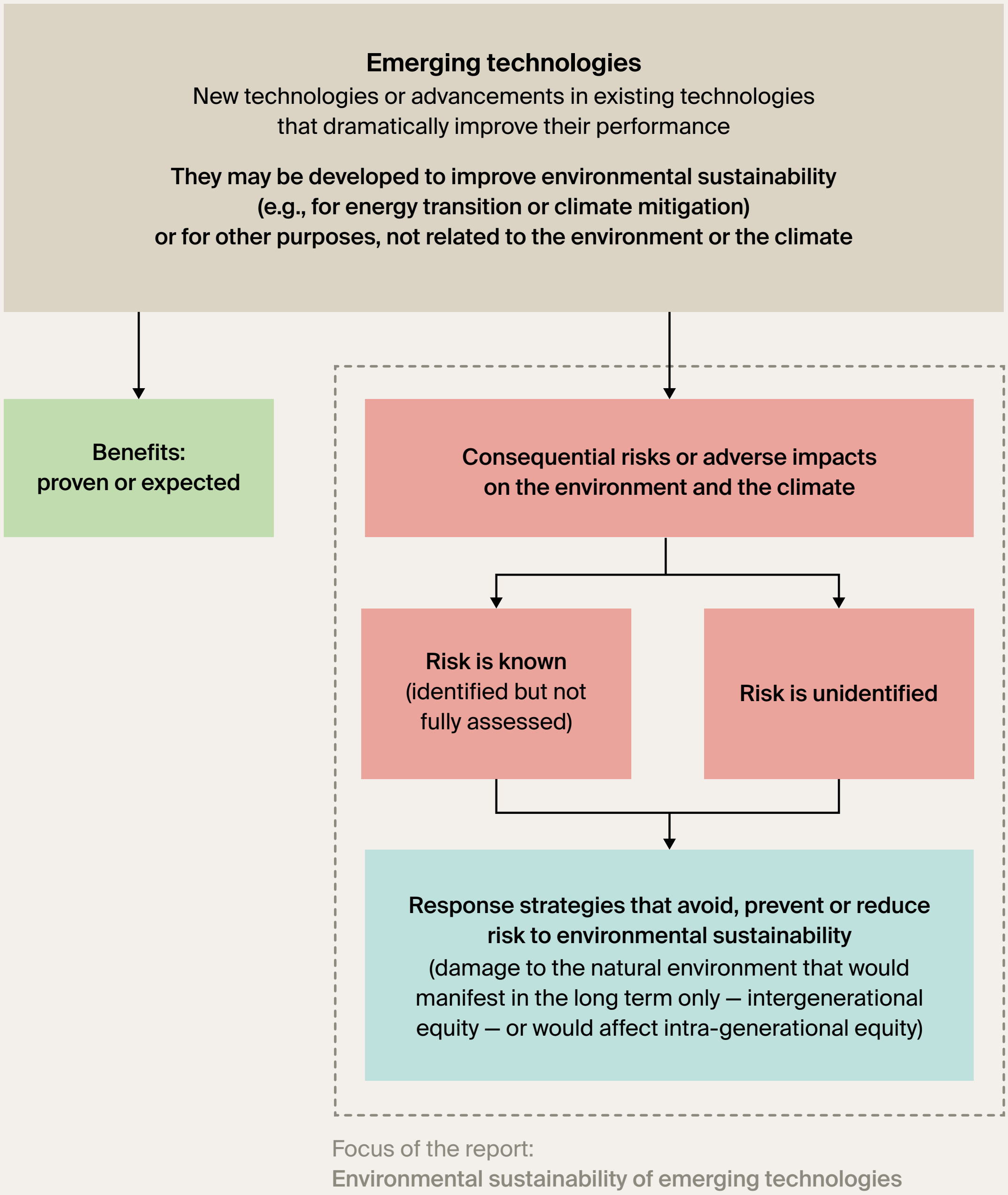

Figure 2 | Ensuring the environmental sustainability of emerging technologies: Framing and key elements

Chapter 1

Environmental sustainability of emerging technologies

This chapter describes various aspects of the concepts of environmental sustainability and emerging technologies, as well as the focus of the report, presented in Figure 2.

1.

Environmental sustainability

Technology for sustainability and the sustainability of technologies

The importance of developing technologies for combatting climate change, for environmental protection or remediation and, more broadly, for environmental sustainability has been demonstrated in recent years. Strong incentives and increasing attention from policymakers to encourage and invest in “green” technologies and to support “sustainable finance” to meet the expectations of governments, investors and the public, may lead to technologies being promoted and pursued without complete risk assessments or due consideration of the possible undesirable side effects. Such a rush to find solutions to immediate problems may overlook the full extent of the consequences. A case in point is the encouragement to adopt electric vehicles before conditions for the sustainable mining of rare earth elements are established or before large-scale plans for battery waste disposal and recycling are in place.

Significant attention has been drawn to a technology's possible adverse effects on societal and ethical aspects, when its application may lead to adverse consequences to fundamental principles or rights, such as privacy and democracy. But is enough attention being paid to the risk that an emerging technology could cause indirect damage to the natural environment or the climate? "Adverse outcomes of technological advances" is one of the 37 risks monitored by the World Economic Forum in its annual Global Risks Report, with this risk defined as "intended or unintended negative consequences of technological advances on individuals, businesses, ecosystems and/or economies," (World Economic Forum, 2021) with examples given from artificial intelligence (AI), brain-computer interfaces, biotechnology, geo-engineering, quantum computing and others.

Similarly, caution is required before substituting harmful chemicals, whose risks are well known, with more advanced chemicals whose full range of effects are not yet well understood. Regulators will have to assess and resolve ex-ante trade-offs between, on the one hand, the promise of these new chemicals for higher efficiency and performance and, on the other hand, uncertainty about potential adverse effects that may appear in the longer term, perhaps outside of the intended use. Another example is that great promises of "AI for sustainability" may hide that AI itself is not always environmentally sustainable and operators may fail to account for the environmental impact of AI development (van Wynsberghe, 2021).

Emerging technologies offer a multitude of trade-offs between their beneficial and adverse consequences on the environment. The balance will depend on how narrowly or widely the net is cast to identify applications and their implications, the time horizon considered, and the technologies' specific characteristics. Acknowledging that a generalisation is not possible, this report sketches the contours of more targeted investigations that would need to be undertaken before drawing any final conclusion.

Environmental sustainability

Sustainability is defined as the ability to meet today's needs without compromising long-term needs related to the environment, society and the economy. This conception of sustainability was established in "Our common future," a report from the Brundtland commission to the United Nations Framework Convention on Climate Change in 1987 (World Commission on Environment and Development, 1987). The UN Sustainable Development Goals (SDGs) embed these principles into goals (UN General Assembly, 2015), and the European Green Deal establishes a roadmap to sustainability in Europe (EC, 2019). Regarding risk to sustainability, a report from Swiss Re describes it as follows: "In a properly regulated market environment, profitable business activities create economic value. Occasionally, however, they may also adversely affect people and the environment. If such impacts are ignored, they may pose a threat to societies' long-term sustainable development" (Swiss Re, 2016).

This report focuses on two main aspects:[1]

- Environmental sustainability, which includes challenges related to biodiversity, ecosystems and the services they provide, the use of natural resources, and climate, which can be adversely affected by the development of technologies and their applications in various domains;
- Potential damage to the natural environment that would manifest in the medium to long term (i.e., not immediately) as a result of a new technology being deployed.

The drivers or changes relevant to the environment and sustainability can be grouped into six clusters: (i) a growing, urbanising and migrating global population; (ii) climate change and environmental degradation worldwide; (iii) the increasing scarcity of and global competition for resources; (iv) the acceleration of technological change and convergence; (v) power shifts in the global economy and geopolitical landscape; and (vi) the diversity of values, lifestyles and governance approaches (Benini & Viaud, 2019). Understanding these drivers can inform ongoing, emerging and potential future developments, raise awareness and contribute to the diffusion of anticipatory thinking.

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[1] In some cases, this report may also include broader challenges affecting intra-generational and intergenerational equity, responsible research and innovation (RRI; see p. 28), ethics, or fairness in general. However, the workshop focused on the environment and did not include in-depth consideration of society and the economy.

2.

Emerging technologies

Emerging technologies are new technologies or advancements in existing technologies that dramatically improve their performance. Some can disrupt existing industrial processes or contribute to fundamental changes in the economy and society. Five attributes characterise emerging technologies: (i) radical novelty; (ii) relatively fast growth; (iii) coherence; (iv) prominent impact; and (v) uncertainty and ambiguity (see Rotolo et al., 2015). Emerging technologies pose unique challenges to risk assessors and managers because of a general lack of procedures and tools to assess their potential impact, and insufficient data on which to build evidence. Uncertainty (the absence of sufficient evidence) pertains to both how the technology will first be developed and how it will be deployed in the market. The ambiguity is due to diverging views resulting from diverse interests. In a nutshell, it is very difficult to anticipate an emerging technology's breadth of application.

Technology readiness level

The concept of technology readiness level (TRL) and manufacturing readiness level (MRL) can be useful to characterise the maturity of technologies (NASA, 2021). TRL is a qualitative scaling method ranging from 1 (basic principles observed) to 9 (actual system proven in operational environment). MRL is similar to TRL but encompasses components and subsystems of the technology from a manufacturing perspective. The type of impact or risk assessment that is possible for an existing technological product (i.e., at high TRL) is rarely possible at the early stages of its development (i.e., at low TRL).

At low TRL, the data and tools to assess the potential impacts are lacking and the ability to change the technology's design is considerable. At a higher TRL, more data and tools are appropriate to assess the potential impacts, and therefore the impacts are more certain, but flexibility and the ability to change the technology's design are reduced. Thus, the trade-off is between making a decision with insufficient evidence and waiting until it may no longer be possible to change a technology's design (Collingridge, 1980), which is illustrated in Figure 3. This is one of the challenges to ensuring the environmental sustainability of an emerging technology.

Furthermore, the specific products or applications that researchers typically have in mind when developing a new technology will often be repurposed to new applications. Hence, the challenge is to anticipate negative impacts overall.

The changing nature and convergence of technologies

Disruptive advances have occurred in recent years in the development of complex compound materials and converging technologies that integrate elements from different sources and disciplines (e.g., engineering and life sciences) for applications in diverse sectors, to create novel mechanisms

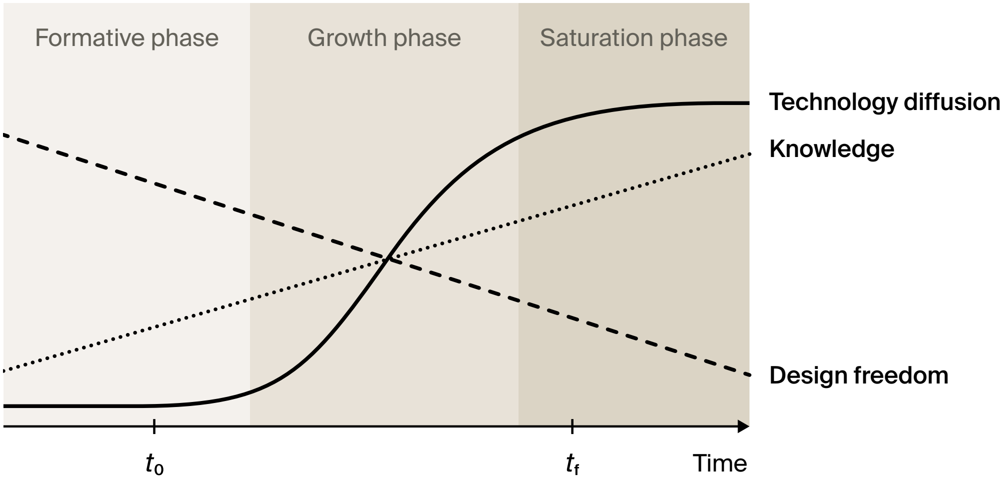

Figure 3 | Environmental assessment of emerging technologies (reprinted from Arvidsson et al., 2018)

or organisms with unique performances. Certain technologies produce active systems that adapt and change in response to external stimuli, for instance in the case of smart nanomaterials. Many emerging technologies are so-called post-containment technologies, which are actually built not to be contained and that owe their societal value and business opportunity to the very fact that they evolve in response to external conditions and are very pervasive, spreading to and influencing every part of society. They can adapt to different contexts and situations. These technologies are problematic for risk assessors who may not have the appropriate tools to evaluate them, and for regulators when the applications do not fit existing regulatory frameworks. They often present new challenges for waste management and recycling, which may pose a risk to long-term environmental sustainability.

Emerging risks

With emerging technologies come emerging opportunities, in terms of industry and product performance and cost-efficiencies, new markets and business, but also emerging risks. IRGC defines emerging risks as new risks or familiar risks that become apparent in new or unfamiliar conditions. This definition suggests that assessors need to focus on analysing contributing factors to risk emergence and emerging risks' triggers, foresight and early detection, while managers should focus on the impact side and reducing exposure to possible emerging risks. As the concept of emerging risk is relative, not absolute, risks that may be familiar to some may be new to others. The major characteristic of an emerging risk is uncertainty, i.e., a lack of or insufficient knowledge about source and impact (IRGC, 2015).

Chapter 2

Matters of concern

This chapter lists several key themes that arose during the workshop discussions, which are issues of concern. Many are generic challenges faced in complex science, policy and industry matters. They increase the complexity and difficulty of guiding technology research and development towards positive environmental outcomes and of ensuring the long-term environmental sustainability of emerging technologies' future applications or their outcomes.

Uncertainty about the anticipated outcome of an emerging technology

Instead of passing an overall judgement on an emerging technology, it is necessary to look at its fundamental design, which may determine future characteristics, and at the anticipated outcomes of its applications, often on a case-by-case basis. A new technology's outcomes are often uncertain and may change between the time it appears as just an idea and the time it is used in a product, manufactured and placed on the market. Moreover, value systems evolve over time, affecting risk perceptions and technology assessments. In the face of promising (but uncertain) applications and potential risks, balancing their benefits and costs, or innovation and precaution, is not a simple technical exercise, but one that requires various stakeholders with different perspectives on the technology and its possible functions and outcomes.

Lack of instruments to assess sustainability

Although the concept of sustainability is theoretically well defined, translating it into actionable assessment tools and metrics is challenging. Sustainability can become vague when it comes to designing criteria, indicators or processes for its materialisation in the physical world. Moreover, it does not apply well to individual products, and requires a systems approach to assign the benefits and risks to various actors across the supply chain. Environmental sustainability is a multidimensional concept that requires its potential trade-offs to be addressed and that makes the establishment of actionable tools and metrics difficult.

Risk of unsustainable solutions to immediate problems

Long-term environmental sustainability risks can be created and neglected in the rush to implement solutions that deal with well-identified problems. Although response strategies to pressing issues must be developed, rushing to solutions without a sufficient ex-ante evaluation of the proposed resolutions' potential risks and related uncertainties would be a mistake. In some cases, the cure may even be worse than the disease. For example, climate change is such a serious concern that developers worldwide are working hard to develop technologies that can reduce the cause (excess atmospheric concentrations of greenhouse gases) and some of its most severe consequences. However, certain techniques to reduce CO_2 emissions and remove CO_2 from the atmosphere could have undesirable adverse effects on the environment, some of which could become visible only in the long term.

Temporal issues and biases

Temporal issues and biases complicate matters. Governments and industries struggle when they have to invest for possible returns in the future, and there is no consensual system for internalising the negative externalities that may only manifest in the long term. History is full of examples of possible environmental or climate damage that was flagged, but nothing or not enough was done to prevent their manifestation. The most well-known example is the burning of fossil fuels that causes climate change. But in some rare cases, action was taken to limit environmental damage, such as the ratification of the Montreal Protocol, where the world's countries decided to ban chlorofluorocarbons (CFCs) based on evidence that their use was causing the destruction of the ozone layer.

Scholars have shown that people discount the future for several very defensible reasons and that a range of cognitive and organisational biases explain why humans and organisations are not good at preventing something bad from happening in the future. This is the case, for example, when people are not personally adversely affected (the impact is far away from them in space or time); when the cause–effect relationship and attribution are not supported by sufficient evidence (proof is missing or evidence is contested and principles such as the polluter pays principle cannot apply); or when a legal exemption authorises the activity that causes the risk. Both uncertainty and ambiguity are major obstacles to implementing sustainability initiatives and developing specific regulation that enables a technology to produce benefits while managing its risk.

Limitations of the conventional containment approach to risk management

The traditional containment approach that consists of developing ways to prevent a risk's materialisation and reduce its consequences remains effective in several technology domains or applications. But it becomes challenging with new technologies that diffuse and change with use, suggesting that the traditional assessment and management approaches have reached their limits. This is clearly the case with advanced synthetic biology, where the major feature of gene drives is to propagate through inheritance, or with smart nanomaterials that respond to external stimuli. The digital world can also be seen as an environment in which risk to cyber-security propagates within systems, and traditional approaches to stop the spread of cyber-attacks through firewalls and anti-viruses have reached their limits.

The time when it was possible to think about containing a technology has passed, and the current era in which technologies become foundational to a range of possible applications and functions has implications for risk management. It means that the strategy that consists of controlling risk may become inefficient. Hazards are no longer bounded. Targeted control interventions remain possible and should be identified (for example, the possible existence of on-off kill switches or thresholds that can start or stop the propagation of genetically engineered mosquitoes) but often the systemic nature of risk will require assessing the future outcome of technologies in various scenarios at a systems level, and intervening on the system itself. This also means that risk managers need to move to uncertainty management. Tension exists between insufficient evidence and the necessity to make decisions, so risk managers' first tasks will be to monitor emerging technologies and to build up a continuous and iterative process to assess and manage them.

Disagreement in society about what represents a risk to environmental sustainability

The changing nature of some emerging technologies also implies that evaluating their risks depends on a set of broader perspectives, including from society, which should be involved in decision-making about what is desirable and what is not. The balancing of the costs and benefits requires a wider social appraisal of risk that takes into account multiple impacts, co-benefits and related trade-offs. This can be particularly challenging with some issues like planetary-scale interventions to mitigate climate change that include carbon dioxide removal, where the risk of deploying the technique (including long-term risks to ecosystems and environmental sustainability) must be balanced with the risk of not deploying it (the increased cost of climate change).

Making a judgement about whether a technology application is sustainable is a by-product of technical, social and political processes. It goes beyond evaluating knowledge or using a framework, even though these are needed. It involves strengthening certain skills, such as openness to non-technical matters, within the process of developing a technology.

In democratic societies, the public may not agree with those who decide that something is hazardous. For example, in the case of water and soil contaminated by radiation from the Fukushima nuclear accident, no consensus has been reached on the severity of harm and threat to long-term sustainability. Even for a traditional technology like nuclear power, no global societal agreement exists about whether it may cause long-term risks to environmental sustainability. In another case, genetic engineering techniques like CRISPR-Cas, a multiplicity of types and levels of risk assessments may provide very different conclusions. In that context, and as discussed in Chapter 4, the regulatory process is extremely important.

The pacing problem of regulation

Some tension between insufficient evidence and the necessity to make decisions occurs often. In particular, it is hard for regulators to keep pace with innovation and accompany the deployment of new technologies with appropriate regulations. Technology develops much faster than regulation, and societal preferences or behaviour regarding a new technology may not be aligned with regulatory requirements. When knowledge is incomplete, regulators who need scientific evidence to support their decisions may delay decisions, or prohibit, ban or temporarily authorise the use of the technology on the condition that authorisation will be revised once more evidence is collected. The presence of scientific uncertainty suggests the use of mechanisms for decisions under uncertainty, which regulators are not always comfortable with. Chapter 4 discusses ways to introduce adaptability in regulation.

Insufficient moral and ethical guidance

There are links between environmental concerns and matters of ethics, responsibility, liability, responsible research and innovation (RRI; see p. 28), which may provide the rationale and support for making decisions about uncertain environmental concerns. However, moral and ethical considerations do not always guide research priorities, and environmental sustainability may be neglected. In the absence of such considerations, the default approach becomes that if something can be developed, someone will do it.

Chapter 3

Cross-sectoral aspects in five technology domains

The first section of this chapter provides background on our rationale for considering the environmental sustainability of emerging technologies for certain specific aspects or applications in five domains: chemicals and advanced materials, synthetic biology, digital technologies, carbon dioxide removal and sequestration, and space technologies. The second section highlights the aspects featured during the workshop discussions as possibly useful to guide the development of ways to assess and manage environmental sustainability. The third section presents a brief comparative analysis of the current attitude and approaches to governing environmental sustainability risk in each technology domain.

Appendix 1 (*Technology domains*) provides background information on the concerns associated with certain emerging technologies and possible ways to address them. It includes detailed reports of the workshop discussions in the five technology domains.

1.

Background: Reasons for interest in certain technology domains

Chemicals: Advanced materials and smart nanomaterials

New chemicals and advanced materials that improve performance and efficiency may raise concerns about potential long-term environmental damage if they end up in the terrestrial or marine ecosystems. The long-term challenges are associated with uncertainty about the environmental impacts of future technological developments, such as with so-called smart nanomaterials (active nano-based products and systems whose function changes in response to external stimuli). Concerns also exist about the lack of tools and data to conduct environmental assessments of many advanced materials.

↦ See Appendix 1.1, p. 37

Synthetic biology: Gene editing and gene drives

Synthetic biology, in particular gene editing and gene drives, can significantly benefit public health, agriculture, environmental remediation and biodiversity conservation. However, it can also cause substantial knock-on effects on conservation, including modified genes spreading to non-target populations and food webs affecting broader ecosystems. As a result, it is often contested within the environmental expert communities. Evidence is lacking on the long-term impacts after release in the natural environment, limiting the ability to evaluate the risk–benefit trade-offs, which makes the early governance of deployment challenging.

↦ See Appendix 1.2, p. 41

Digital technologies: Machine learning, cloud computing and blockchain

Digital technology applications can help to reduce stress on the environment in specific domains. They also raise concerns, however, about their environmental and climate impacts, such as their electricity consumption, use of natural resources, mining of rare earth elements, and waste disposal and recycling. Efforts are under way to measure and report on the carbon footprint of certain applications. The balancing of benefits and risks is particularly challenging, considering the many opportunities offered by digital technologies to contribute to the SDGs.

↦ See Appendix 1.3, page 44

Carbon dioxide removal and sequestration

Carbon dioxide removal (CDR) is being developed to reduce atmospheric CO_2 concentration, thus mitigating climate change. Its deployment through negative emission technologies is necessary to reach the current climate goals, i.e., to neutralise residual greenhouse gas emissions to achieve net zero. However, a range of uncertainties are associated with the various CDR approaches, whether nature-based, engineered or hybrid. Adverse consequences on biodiversity, ecosystems and human systems are among the risks, and some of the sequestration of the CO_2 in various reservoirs could be reversed. Some potentially important effects have already been identified if the techniques are deployed on a large scale. Because of their apparent necessity and the flurry of investments to address climate change, some technologies may be used and expanded without a full assessment of their second-order impacts on the environment (or the climate itself).

↦ See Appendix 1.4, page 49

Space technologies

Outer space is increasingly used by satellite operators to deliver critical services on Earth, including environmental monitoring. However, the increasing risk of collision between satellites and orbital debris, as well as adverse consequences of space activities on the atmosphere, could prevent the sustainable use of space in the long term. The growing space infrastructure is both an asset to improve sustainability on Earth and a cause for concern regarding sustainability in space.

↦ See Appendix 1.5, page 53

2.

Cross-sectoral aspects to consider

During the analytical work before, during and after the workshop, the following aspects have appeared most prominently as being potentially useful for the next work streams towards offering some guidance to those who want to ensure the environmental sustainability of particular technology applications. Further research is needed to confirm their relevance or usefulness.

Benefits and risks from the technology can be public or private, global or local

Emerging technologies can be characterised by the economic properties — rivalrousness and excludability — of their applications.[2] These properties determine whether the expected benefits will accrue mostly to the public or to private actors. The economic properties of emerging technologies' applications affect the distribution of benefits and risks across society and thus can give insight into the feasibility of different policy approaches to ensure their long-term environmental sustainability. These properties are especially important when it comes to addressing externalities.

When emerging technologies lead to excludable applications, their benefits can be reaped by a limited number of actors. These benefits have to be weighed against the long-term risks, which are usually borne by the public at large. Some technologies, such as CDR and gene drives, produce services that have the features of a public good (i.e., they are non-rivalrous and non-excludable). In such cases, the trade-offs are generally between the long-term benefits and risks to the public at large. Other technology domains, such as digital, chemicals and space, develop products and services that are at least partially excludable. Products developed by the chemical industry are generally rivalrous (private goods), while services provided by satellites are non-rivalrous (club goods).[3] Digital technologies include goods and services that are either non-rivalrous (e.g., social media) or rivalrous (e.g., processors). As a result, the trade-offs to resolve before deploying the technology are generally between the short-term benefits to private actors and the long-term risks to the public.

Benefits and risks can be global or local. Governance systems to govern risks will need to adapt to each case. For example, the benefits and risks from chemicals are primarily local, whereas the benefits of CDR are global and the risks are primarily local or regional.

A technology can be applied or foundational

Applied technologies are generally close to end-users, who can be involved in their governance, for example by indicating their preference in terms of specific products or services that can be labelled or certified for their environmental sustainability. Emerging foundational technologies, such as advanced materials or distributed ledger technology, are those that could enable progress and applications in a variety of problem domains. Life-cycle assessments or technology assessments to evaluate the risk to environmental sustainability may be possible for emerging applied technology, but with large obstacles and uncertainties for upstream foundational technologies.

The use of a technology can be essential or non-essential

An essential technology (i.e., a technology whose use is critical to providing crucial food, water, energy, health and financial services) should be evaluated differently regarding its environmental sustainability than a non-essential technology. In general, an essential emerging technology should be one that the world absolutely needs because there is no alternative, and its anticipated adverse consequences are deemed to be acceptable in view of its expected benefits. In the case of machine

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[2] These properties are not binary but are part of a continuum (e.g., a good's excludability can range from fully non-excludable to fully excludable, with variations in between).

[3] Satellite services that are provided free of charge by the state are more of a public good.

learning, for example, due to the energy needs for training algorithms, it has been suggested that the cost of some non-essential machine learning applications should be higher than those for critical services. Such a proposal would have to be nuanced and consider the environmental footprint of the electricity used in each case. The potential use of regulatory intervention to raise the cost of a non-essential technology that scores low on a list of environmental sustainability criteria should be considered. Yet, the regulatory risk assessment and decision should be made early if they are determined to be important success factors for future deployment in the market. The definition of criteria to regulate emerging technologies on their essentiality is challenging due to the need to make subjective decisions about what is considered essential. Essentiality criteria would have to be defined considering the views of a wide variety of stakeholders, and agreement might be hard to reach.

Environmental impacts can result from energy consumption or effects on ecosystems

The energy needed for a certain technology can cause a range of environmental risks, primarily depending on the energy source: fossil (e.g., coal, oil, gas) or non-fossil (e.g., wind, hydro, solar). In some technology domains, such as digital technology, the energy source and amount consumed can be a major source of risk to environmental sustainability while in other technology domains, such as chemicals or synthetic biology, the risks are dominated by direct and indirect impacts on ecosystems. For carbon dioxide removal, both sources of risk can play a major role, depending on the specific approach taken.

Cause–effect relationships can be hard to identify

It is often difficult to determine the cause–effect relationship between an emerging technology's future products or applications and the deterioration of the environment. Without clear attribution of an effect to its cause, any evaluation should be taken with caution. In principle, all types of responsibility (including reputational responsibility and liability) require clear attribution of harm. This may be possible with chemical products, but is much less evident with digital technologies.

3.

A comparative analysis in five technology domains

Based on discussions in breakout groups and selected insights from research, certain approaches or themes have been found to be either cutting across the five technology domains, or differentiating them.

Table 1 | Comparative analysis of the current approaches to governing environmental sustainability risks in five technology domains

	Chemicals Advanced materials and smart nanotechnologies	**Synthetic biology** Gene editing and gene drives	**Digital technologies** Machine learning, cloud computing and blockchain	**Carbon dioxide removal (CDR)** Removal and sequestration	**Space technologies** Manufacturing, launch, operations and end-of-life
Technological innovation can help society reach its sustainability goals (technology for environmental sustainability), but emerging technologies can cause environmental issues of their own (environmental sustainability of technology)					
The risk to environmental sustainability primarily (although not exclusively) comes as:	• Countervailing risks, traded against benefits elsewhere	• Reduction of expected benefits (synthetic biology for environmental protection or remediation) • Countervailing risks to ecosystems	• Countervailing risks, traded against benefits elsewhere	• Reduction of expected benefits (CDR reduces CO_2 atmospheric concentration) • Countervailing risks to ecosystems	• Countervailing risks, traded against benefits elsewhere
Do private actors enjoy short-term benefits while the public bears the long-term costs? Are the outcomes of a technology a public or a private good?					
Main status of benefits	Private	Public	Private / Public	Public	Private / Public
Main status of risks	Public	Public	Public	Public	Public
What approach is taken in the field to discuss (or not) the question of emerging technologies' environmental sustainability?					
■ **Status of the theme**[4] In general, is the question of environmental sustainability: • Central to current policy? • Occasionally mentioned? • Mainly outside of current interest?	Central • e.g., 2020 EU Chemicals Strategy for Sustainability • But a possible mismatch exists between the motivations of technology developers and policy expectations	Central • Direct and indirect impacts to ecosystems and biodiversity are a key concern	Mainly outside • The awareness of risks is broad but there is no incentive and a lack of data to mitigate them • In case of environmental attention: the negative externalities are "offshored"	Occasionally mentioned • It is increasingly seen as a matter of concern, as it becomes clearer that CDR will have to be deployed on a large scale	Occasionally mentioned • It is mainly in the context of space debris collision risk • Space technologies are exempt from key environmental legislative and regulatory instruments
■ **Assessment: Work to identify possible threats (foresight)**	• Lack of tools and data • Early warning, expert elicitation • Current interest for: prospective life-cycle assessments, early-stage technology assessments, comprehensive supply chain assessment	• Several instruments available in the literature • But scientific uncertainty about the behaviour of living organisms in open environments	• Helpful life-cycle assessments, but lack of data and complexity (multiple forms of emissions, resource extraction and consumption, and recycling) • Lack of methods to anticipate consequences	• Lack of tools and data • Difficulty evaluating life-cycle assessment outcomes • Difficulty assessing permanence of CO_2 storage in nature-based solutions	• Complexity of models and uncertainty about actors' behaviours • Limited evaluation of environmental risks • Life-cycle assessments of individual space missions, but unrobust techniques

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[4] Think (or not) in terms of the need to ensure that the outcome of an emerging technology (or its applications) does not cause damage to long-term environmental sustainability.

	Chemicals Advanced materials and smart nanotechnologies	**Synthetic biology** Gene editing and gene drives	**Digital technologies** Machine learning, cloud computing and blockchain	**Carbon dioxide removal (CDR)** Removal and sequestration	**Space technologies** Manufacturing, launch, operations and end-of-life
What approach is taken in the field to discuss (or not) the question of emerging technologies' environmental sustainability?					
■ **Management: Develop suitable technical instruments and governance mechanisms**	• Lack of tools and incentives, insufficient dedicated regulation • Sustainability-by-design • Circularity	• Focus on technical designs to stop the propagation of a species modified by gene drives	• Sustainability-by-design: a desirous goal, yet unclear instruments and approaches	• Choice of instrument: may depend on the technique • Performance-based regulation and incentives	• European Space Agency at the forefront of developing sustainability principles and tools • Limited other efforts
■ **Balance short-term expected benefits and long-term possible costs**	• Pressure to address currently identified problems, leading to neglecting long-term countervailing risks	• Commonly framing benefits and costs as long term • The evolution of values that support the evaluation of what is desirable or not	• Focus on short-term benefits; regulators limited by the risk of "offshoring" • Consumers uninformed and uninvolved	• The need to develop CDR fast and at scale, leading to prioritising the short term	• Little balance between benefits and environmental impacts • But some pressure applied through public concerns
■ **Differentiate ethical concerns from environmental concerns**	• Not a particular concern, but developing a culture of ethics and responsibility can help	• Ethical and environmental aspects should align • Some ethical norms are contested	• An increase in costs from sustainability requirements would hamper efforts to bridge the digital divide	• The moral hazard concern is prominent and should be addressed	• Ethical aspects regarding sharing benefits from space are included in international discussions • But they seem to be separated from environmental concerns
■ **Educate researchers, technologists and investors (industry and finance)**	• Within the context of balancing innovation and risk management	• Already well established	• Common approach across industries and countries needed to communicate environmental sustainability	• Transdisciplinary research and multi-stakeholder involvement • Lessons to be learned from small-scale experimentations	• Space sustainability is established as a concept but probably not in education and among investors

	Chemicals Advanced materials and smart nanotechnologies	**Synthetic biology** Gene editing and gene drives	**Digital technologies** Machine learning, cloud computing and blockchain	**Carbon dioxide removal (CDR)** Removal and sequestration	**Space technologies** Manufacturing, launch, operations and end-of-life
Concerns about indirect environmental risks that could evolve if the emerging technology is implemented in new products or processes					
Which specific risks or concerns require further study?	• Materials with active or adaptive properties that change in response to stimuli	• Gene drive organisms that could pose significant risk to ecosystems or biodiversity • Diverging opinions about what constitutes an environmental harm	• The increasing requirements of computing power and related externalities (e.g., recycling and reuse)	• The permanency of CO_2 storage (risk of reversal or leakage) • Threats to biodiversity • Competition for other land and energy uses	• Impacts of launches and re-entries on the atmosphere • Space debris • Taking into account the full supply chain, from raw materials to end-of-life
Which specific applications or prospective products?	• Environmental remediation • Agriculture	• Human and environmental health	• The delineation of non-essential applications to potentially raise their costs through regulatory interventions	• Technology-based CDR that seems to generate less concern than nature-based approaches • Nature-based approaches that seem more acceptable to the public	• Environmental impacts that will grow significantly with increased access to and use of space • Impacts that are more related to scale than to specific applications
How can decision-makers include the consideration of long-term adverse environmental impacts in their decisions?	• Work to assess products and processes within their supply chain • Adopt a systems view • Consider assigning responsibility for end-product environmental sustainability	• Use methods to identify possible threats as bases for regulation • Investigate ways to ensure new technologies are not governed by suboptimal legacy regulations	• Collect and share data about the environmental impacts to benchmark applications • Evaluate socio-economic benefits against environmental risks	• Support research to reduce uncertainty • Organise deliberations about priorities to resolve trade-offs • Incentivise and regulate based on the maximisation of potential and the minimisation of risk	• Support research to provide the evidence needed to regulate the most harmful sources of environmental risk • Request disclosures of life-cycle assessment outcomes and carbon footprints
Where are new approaches and instruments most needed to account for long-term impacts, or which instruments should be improved?	• Prospective life-cycle assessments • Regular sustainability assessments analogous to process safety assessments • Early-stage technology assessments • Comprehensive supply chain assessments • Agile and adaptive regulation	• Millennium Ecosystem Assessment framework • Environmental impact assessment • Liability for harm	• Prospective life-cycle assessments • Coordinated response to address “offshoring” • Nudging of good practices • Certification and standards	• Life-cycle assessments • “Net effectiveness” metrics • Certification, standards and policy frameworks	• Greater access to data • Life-cycle assessments • Rating systems • “Environmental capacity” metrics • Product environmental footprint

Chapter 4

Response strategies

This chapter provides brief descriptions of employed or considered response strategies, grouped under two broad and interconnected types: supporting technical concepts and instruments, and ensuring governance and regulation.

1.

Supporting technical concepts and instruments

Instruments to assess and address emerging risks include foresight exercises (narratives of possible futures), horizon scanning and early warning systems to identify signals of upcoming changes. Environmental risks and their impacts are usually assessed through environmental impact assessments, environmental footprints and life-cycle assessments (LCA).

Technologies and products are generally appraised through technology assessments (TA) and cost–benefit assessments. A foresight-based policy analysis is routinely used to inform technology assessment (GAO, 2018; Woensel, 2021).

To evaluate the environmental sustainability of emerging technology applications, ongoing efforts focus on early-stage technology assessments, prospective or ex-ante LCA, and sustainability-by-design (SbD), which this section focuses on.

Early-stage technology assessment

While technology assessment is widely used as a method to inform policymakers and is often part of regulatory requirements, its adaptation to emerging technologies, as “early-stage TA” is less frequent. The main rationale for early-stage TA is that sustainability should not be prescribed or considered only after the technology has been deployed in actual products. Fundamental criteria for sustainability should be considered as early as possible in the development of new technologies (Austrian Academy of Sciences, n.d.).

Early-stage TA relies on the development of concrete approaches and tools for foresight to produce narratives of possible futures and on the prerequisite of neutrality. However, when developed to inform public policy, normative aspects become important. Often the TA process is set up to assess the capability of a certain technology to achieve a certain policy goal, such as sustainability (Nierling & Torgersen, 2019), and indeed some technologies can contribute to environmental sustainability better than others.

Prospective life-cycle assessment of emerging technologies

Interest in LCAs for emerging technologies is growing. However, this method is limited by the lack of available data when technologies are not mature, and by the difficulty to anticipate both how the technology will evolve and how the market in which it will be deployed will develop. In addition, there are gaps in the guidance for practitioners. These limitations are not particular to LCAs and are common to methods addressing technologies' long-term environmental impacts. A major complication when assessing emerging technologies is that their outcomes and the process to produce these outcomes might evolve over time, limiting the ability to compare and make informed decisions.

Principles of life-cycle assessment

Life-cycle assessment or analysis is a method to quantify the environmental impacts of a product, material, process or activity (US Environmental Protection Agency, 2006). It is a cradle-to-grave approach that evaluates all stages of a product's life cycle and estimates the cumulative environmental impacts. The results of an LCA can help policymakers and decision-makers in industry and other areas make more informed decisions to advance towards sustainability.

The LCA process consists of four components (US Environmental Protection Agency, 2006):

1. Goal definition and scoping – Define and describe the product, process or activity. Identify the boundaries and environmental effects to be reviewed for the assessment.
2. Inventory analysis – Identify and quantify energy, water and materials usage, and environmental releases (e.g., air emissions, solid waste disposal).
3. Impact assessment – Assess the potential human and ecological effects of energy, water and material usage, and the environmental releases identified in the inventory analysis.
4. Interpretation – Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

The standardisation of LCA methods has sought to maintain flexibility while ensuring consistency and clarity in reporting. LCAs produce outcomes whose quality depends on the availability and quality of the data, which are often imperfect, and the underlying value system (i.e., the LCA's objective).

Challenges in the prospective life-cycle assessment of emerging technologies

The fundamental approach of an LCA is the same when applied to existing and emerging technologies. However, conducting a prospective or ex-ante LCA of an emerging technology (see Figure 4) involves: (i) scaling up the emerging technology using likely scenarios of future performance at full operational scale; and (ii) comparing the emerged technology at scale with the evolved incumbent technology (Cucurachi et al., 2018). It thus requires modelling the foreground and background systems at a future time. The foreground system consists of processes under the decision-maker's control for which the LCA is carried out.[5] In contrast, the background system encompasses processes on which the decision-maker can, at best, exercise indirect influence.

The prospective nature of the assessment and uncertainties associated with technologies at an early

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[5] The incumbent technology is also part of the foreground as it is modelled with primary data and is also the focus of the analysis although it is not under the decision-maker's control.

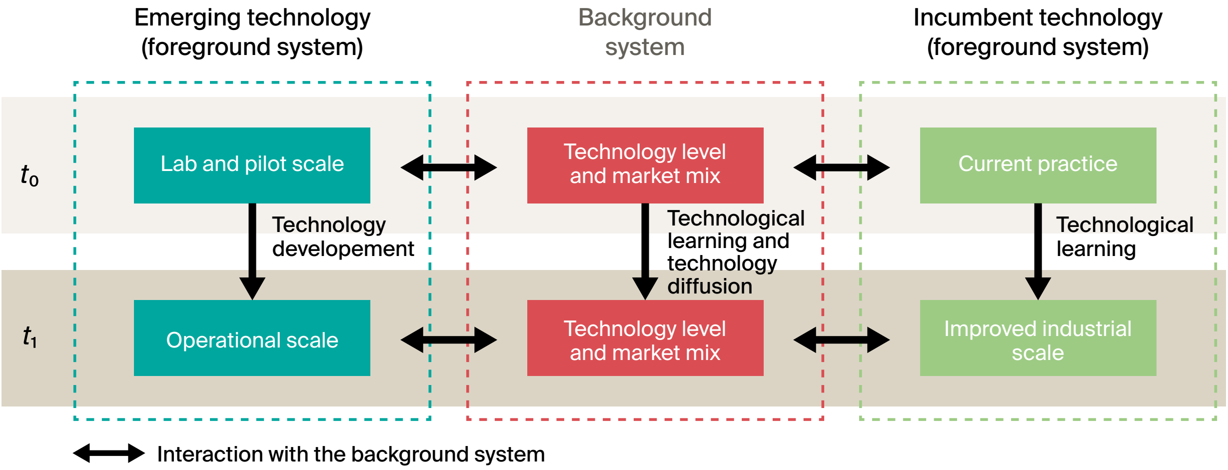

Figure 4 | General framework for ex-ante LCA (adapted from Buyle et al., 2019). Comparison of a scaled-up emerging technology in the future with an incumbent counterpart as a reference

stage of development lead to a range of challenges (see, e.g., Bergerson et al., 2019, 2020; and reviews by Moni et al., 2020; Thonemann et al., 2020).

First, systematic guidance to LCA practitioners to evaluate emerging technologies is lacking. The procedures and tools are not yet well defined and systematised. LCA practitioners lack clear guidance as to what methods are available, applicable or appropriate.[6] Referring to ISO 14040:2006, *Environmental management – Life cycle assessment – Principles and framework*, Moni et al. (2020) note that “existing guidelines of LCA are suitable to determine environmental burdens of technologies at TRL 7–9.” Thus, applying an LCA at low TRL levels (e.g., 2–5) would require methodological advances.

Second, data on emerging technology applications are often scarce or measured in a lab setting, leaving significant uncertainty about the technology’s effect when deployed at scale. The lack of historical data, the confidentiality of industrial processes and the use of novel materials are barriers to analysing the impacts of emerging technologies. Sometimes the tools to assess the environmental impacts of new materials, processes or products are simply missing.

Third, the maturity of a technology or its scale of production can significantly affect the results of an LCA (Moni et al., 2020). Even if sufficient lab-scale data are available, LCA results might not reflect the environmental impact after the technology has scaled up. When comparing an emerging technology to an industrial-scale technology, the use of a scale-up framework, which includes a number of assumptions, is necessary (see Tsoy et al., 2020 for a review of upscaling methods). To model the emerging technology, Arvidsson et al. (2018) suggest using: “(1) predictive scenarios that illustrate environmental impacts given some likely development, including status quo, and (2) scenario ranges that are employed to illustrate the potential environmental impact, including extreme scenarios.”

Fourth, LCA studies are comparative in nature. They require identifying the best available technology performing a similar function as the emerging one in the current technological landscape (Cucurachi et al., 2018). However, many emerging technologies will provide new functions making the comparison difficult using this methodology. Moreover, at low TRL levels, the function of a technology might not be clearly defined, or it might shift through its development or use.

Fifth, uncertainty also exists on how the emerging technology might be deployed and on the market conditions into which it might be deployed. Bergerson et al. (2019) note that the market (i.e.,

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[6] Bergerson, Brandt, et al., (2019) propose a list of questions to pose during the goal and scope definition when conducting an LCA of emerging technologies, which is useful to begin (see their Table 1).

An example of application: The hyperloop

The hyperloop is a proposed high-speed transportation system consisting of sealed vacuum tubes in which pods can travel with limited air friction. It is a good example of an emerging technology that would be deployed in an emerging market (Bergerson et al., 2019). This new transportation mode could lead to lower costs, shorter travel times and higher energy efficiencies. However, its potential unintended consequences and environmental impacts are uncertain. The hyperloop is a disruptive technology because of the high speeds it can reach and its new infrastructure requirements, with potential demand and implications that are very different from existing transportation modes. The technology and market can co-evolve or evolve independently, resulting in different maturity levels. Evaluating such a technology's environmental impacts or sustainability does not only require "performing a bounding analysis and attempting to generate estimates of the material and energy requirements" (e.g., pipeline diameter and thickness, materials to build the pods, energy required for propulsion) but also "involves scenario generation for potential demand" (Bergerson et al., 2019). The latter is more challenging than the former as it requires estimating the extent to which the hyperloop might substitute current travel modes or create new demand and its environmental consequences. In both cases, "it is important to acknowledge the difficulty in adequately anticipating unexpected outcomes or even assessing the level of uncertainty" (Bergerson et al., 2019). Furthermore, the strong radio frequency magnetic fields involved could give rise to health problems.

The hyperloop can lead to co-benefits, such as the reduced use of transport systems that pollute more, and countervailing risks, for example, through rebound effects (e.g., an increase in travel). The disruptive nature of such a technology makes evaluating the wider environmental impacts difficult.

the context) into which a technology is deployed can have different levels of maturity (similarly to the technology assessed). Different market characteristics, such as supporting infrastructure, the availability of material and energy supplies, policy and legal frameworks, and consumer behaviours, can significantly impact LCA results.

Sixth, because the background system must be modelled at a future point in time when the technology assessed is deployed at scale, the challenge is thus to choose an appropriate background system and avoid a temporal mismatch with the modelling of the foreground system.

In conclusion, a major difficulty in applying an LCA to an emerging technology is the uncertainty on both the technology and the market in which it will be deployed. Several methods have been used to address this uncertainty better. They include using sensitivity analyses to help identify key parameters affecting a technology's environmental impacts (e.g., Lacirignola et al., 2017; Ravikumar et al., 2018) and integrated assessment models to develop future demand scenarios (e.g., Mendoza Beltran et al., 2020). Moreover, technological and market uncertainty are interdependent, and some factors can contribute to both. For example, user behaviour can impact technology design and vice versa (Bergerson et al., 2019).

Sustainability-by-design

Following the adoption in the EU of the Circular Economy Action Plan (EC, 2020a) and the new Chemicals Strategy for Sustainability (EC, 2020d), several initiatives were launched to address the need to develop more sustainable technologies and products. There is a particular interest in "sustainability-by-design." A European Commission's report (2021) recommends that the product candidates should be assessed and compared for their life-cycle effects, including four aspects: (i) safety; (ii) resource use and circularity; (iii) greenhouse gas emissions; and (iv) impacts on ecosystems. In the chemical sector, ongoing work aims to develop a "framework for sustainable-by-design that will guide the definition of a set of criteria to increase the safety and sustainability of chemicals, materials and products" (Amodio et al., 2021). The European Environmental Agency (EEA, 2021a) describes steps in the approach to the safe and sustainable design of chemical products, as illustrated in Figure 5, which can be applied.

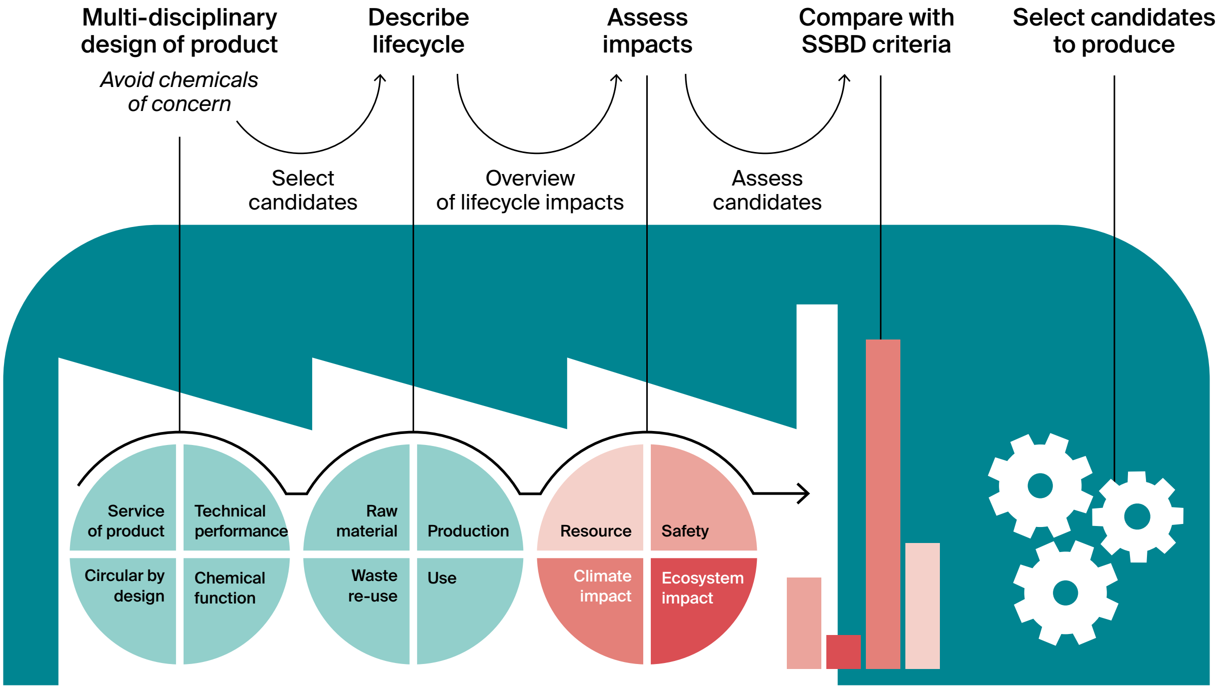

Figure 5 | Implementing safe and sustainable-by-design approaches, in the case of chemicals (adapted from EEA, 2021a)

2.

Ensuring governance and regulation

On the side of governance and regulation, various approaches could be developed to help ensure the environmental sustainability of emerging technology outcomes. This section details some prerequisites (information sharing; awareness, education and reputation; and responsible research and innovation) and then elaborates on some approaches for consideration by legal and financial systems as well as those involved in sustainable finance, funding and grant-making. Particular attention is drawn to the development of standards, the labelling and certification of products; the deployment of circular economies; the adoption of precautionary approaches; adaptive regulation; the revision of responsibility and liability regimes; and the engagement of the judicial system to take on an active role.

Prerequisites

Information sharing on emerging technologies and possible associated risks

Sharing information and communication in relation to emerging technologies or risk is desirable and often required. This is the case, for example, with the "no data no market" principle of the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH, Regulation 1907/2006) regulation in the EU. However, the sharing of information on incidents and irregularities, which could signal an unspotted or emerging deficiency, failure or risk, must be done early and more systematically. Ideally, establishing neutral and independent platforms, or trusted environments, for the stable and continuous sharing of information and communication processes would help. Still, the inclination of knowledge contributors to participate is hampered by an unwillingness to share information that may detract technology development or constrain research.[7]

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[7] See, for example, the European Union Observatory for Nanomaterials (EUON) organised by the European Chemicals Agency (ECHA) at euon.echa.europa.eu.

Awareness, education, consumer behaviour and reputation

A culture of sustainability is rarely part of the early conception of new technologies, which instead is driven by innovation to meet unmet needs (including those of sustainable development and climate change reduction), or market demands for performance, efficiency or consumer preference. Technology development and assessment is a social construct and occurs within a complex social ecosystem in which technology development is affected by society and affects society in a feedback effect.

Education has a role to play in steering developments towards those that make sense for society, the planet and the common good. The kinds of skills that the educational system would be advised to develop – and are needed to participate in the evaluation of the environmental sustainability impacts of emerging technologies – include systems thinking (ability to think in terms of societal, economic and environmental aspects, integrating global and local considerations and cascading effects), future thinking (imagining the future), integrated problem-solving and collaborative capabilities across disciplines. On the industry side, reputational matters can steer more and deeper attention to making business sense of sustainability. On the consumers' side, raising awareness of sustainability challenges can trigger behaviour change so that consumers become actors in their choices.

Responsible research and innovation

Academics and policymakers often refer to responsible innovation in the context of responsible research and innovation (RRI). RRI is defined as “a transparent, interactive process by which societal actors and innovators become mutually responsive to each other with a view to the (ethical) acceptability, [environmental] sustainability and societal desirability of the innovation process and its marketable products” (von Schomberg, 2011, as cited in Yaghmaei & van de Poel, 2020). RRI allows the appropriation of scientific and technological advances by society. Key dimensions of RRI of relevance to environmental sustainability include anticipation (i.e., the ability to foresee possible consequences of innovation), reflexivity (i.e., making values and beliefs in the innovation process more explicit to enable adaptation when necessary), inclusion (i.e., engaging different stakeholders in the early stage of the innovation process), and responsiveness (in the sense that the challenge of responsible innovation is how to improve responsiveness to societal [and environmental] challenges) (Verburg, et al., 2021). RRI might provide a more appropriate paradigm for evaluating new technology than the conventional linear approach to risk assessment, management and regulation, discussed in Chapter 1.

Sometimes the distinction between environmental and ethical concerns is quite thin. This can be the case for gene editing outcomes, where it is not clear whether decisions should be based on the fear of potential damage to the natural environment or the principle that science should not be allowed to modify life. Similarly, the distinction between environmental sustainability and responsibility can also be very thin, and lessons from the research and practice in both fields can be useful.

Standards, labelling, certification and frameworks

It is probably premature to develop standards based on processes and criteria to evaluate and reduce the adverse consequences of an emerging technology on environmental sustainability.

The standards developed by the International Organization for Standardization (ISO) focus on reaching a positive outcome rather than avoiding a negative one. ISO 26000 on social responsibility provides guidance on how an organisation can operate in an ethical and transparent way that contributes to sustainable development, with a positive impact on society and the environment (ISO, 2018). ISO 56000 on innovation management suggests principles to help organisations capture the best ideas and continually improve to keep up with the competition. Still, environmental risk and sustainability are not directly addressed (ISO, 2020).

The International Telecommunication Union (ITU) Focus Group on Environmental Efficiency for Artificial Intelligence and other Emerging Technologies (FG-AI4EE) is worth mentioning for its development of technical reports and specifications to address environmental efficiency as well as the water and energy consumption of emerging technologies to meet the SDGs (ITU, n.d.).

The Roundtable on Sustainable Biomaterials (RSB) has developed sustainability standards, which help biomass producers and consumers to adopt technologies that meet agreed principles and criteria for environmental sustainability.[8] This could be a possible example for other technology domains. Other similar examples include the Marine Stewardship Council and the Forest Stewardship Council.

It is also noteworthy that some product innovation models, such as the Cooper Stage-Gate model,[9] offer a value-creating business process designed to transform ideas into products, taking risk into account.

Circular economies

Businesses are encouraged to develop actions to meet the goals of a circular economy, e.g., reuse, repair and recycle, and appropriate business models, technological innovations and social innovations that are required for that purpose (EC, 2020a; EEA, 2021b). However, many structural issues constrain the scale and impact of circular activities, including that the use of virgin material is often encouraged and even sometimes required by regulation, many components are disconnected, actors on the value chain do not collaborate during the design phase, and targets and metrics are lacking (Yosie, 2021b). The development and use of comprehensive LCAs could enable steps towards circularity and circular economies.

Precautionary approaches vs the need for innovation

Precautionary approaches can lead to policy decisions that delay or ban technologies or products with potentially severe adverse consequences on the environment until sufficient evidence of no harm is produced. Regarding broad sustainability concerns, would or could a precautionary approach be adopted?

Research programmes, such as the EEA's "late lessons from early warnings on the precautionary principle" (EEA, 2001, 2013), have made the case that, with some notable exceptions, and despite great progress on the early identification of possible adverse effects on human health or the natural environment, rarely has a technology developed for expected benefits in one area not been deployed even when there is a threat of damage elsewhere. Cases in which a ban or moratorium was imposed were decided through the application of the precautionary principle, or when the cost–benefit analysis clearly showed that the expected costs would exceed the expected benefits. Today, at least in Europe, various initiatives suggest a review of how the precautionary principle is applied, especially when it is seen as an undue obstacle to innovation. Some of these initiatives aim to reconcile precaution and innovation.

Legal and financial systems

In broad terms, the legal and financial systems can potentially provide support to ensuring the environmental sustainability of emerging technology applications in various ways, including through regulation, liability regimes, judiciary decisions and financial instruments. Laws and regulations are needed and can help in many ways. Regulatory institutions are important because they represent democracy in action. It is where science, society, industry and policy converge to deal with risk as well as social aspirations, including for environmental sustainability. Lawmakers, regulators and judges are those who ultimately resolve the trade-offs between the risks and benefits.

Regulation

Regulatory approaches, including prior risk assessment approaches and similar types of procedures, are ex-ante mechanisms to dictate requirements or provide incentives. Regulators' early consideration of a technology's potential to bring important societal changes, both desirable and undesirable, is a requisite in the face of disruptive, adaptive, pervasive technologies like advanced synthetic biology or digital technologies.

Regarding emerging technologies developed by some actors or for some activities that should probably be regulated according to the risk involved, it is increasingly challenging for regulators to find

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[8] See the Roundtable on Sustainable Biomaterials website at rsb.org.

[9] Information on the Stage-Gate model is available at stage-gate.com.

the right balance between preserving freedom and mitigating risk, or between making rules based on uncertain and changing evidence and waiting until more evidence is collected (which is what some call the "pacing problem"; see, e.g., Marchant et al., 2011; Thierer, 2018). The proposal to regulate AI in the EU is a good example of risk-based regulation for applications of AI technologies, implying that an application that would be categorised as "high-risk" could be lowered to "low-risk" if techniques to reduce the risk are embedded in the technology (EC, 2021).

Planned Adaptive Regulation (PAR) is an approach in which a regulation is designed from its initiation to learn from experience and to be revised over time (Bennear & Wiener, 2019a, 2019b; IRGC, 2016; McCray et al., 2010). It requires planning for future review and revision of the governance arrangements; the funding of targeted research; the monitoring of the performance and impact of existing arrangements; and concrete review and revision. Also necessary is a vision of what the goal of adaptability is; the ability to respond to rapid changes; and trustworthiness between the actors who want to adapt the rules.

PAR could guide regulators and become the by-default framework for regulating specific applications of emerging technologies, until sufficient clarity and certainty are collected through research and experimentation. However, while this makes sense in theory, a range of obstacles and oppositions exist on the side of regulators and industry.

Liability regimes

The workshop explored, although in a limited manner, the extent to which an environmental liability regime could apply to environmental sustainability risk caused by an emerging technology. In the US, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or "Superfund") and the Oil Pollution Act (OPA) establish liability for environmental damage (US Environmental Protection Agency, 2015). In the EU, the Environmental Liability Directive (ELD; *Environmental Liability*, Directive 2004/35/CE) aims to prevent and remedy environmental damage. The ELD is based on the polluter pays principle. Where environmental damage has not yet occurred but the threat of such damage occurring is imminent, the operator shall, without delay, take the necessary preventive measure. The ELD does not require, as a prerequisite, that fault or negligence be established on the part of the operator for them to be held liable. However, the establishment of a causal link between the activity and the damage is always required. The ELD states that "Member States may allow the operator not to bear the cost of remedial actions [...] where he demonstrates that he was not at fault or negligent and that the environmental damage was caused by: (a) an emission or event expressly authorised [...] under applicable national laws and regulations [...]; (b) an emission or activity or any manner of using a product in the course of an activity which the operator demonstrates was not considered likely to cause environmental damage according to the state of scientific and technical knowledge at the time when the emission was released or the activity took place" (*Environmental Liability*, Directive 2004/35/CE). Possible amendments to the ELD could include adding a civil law regime that would create supply chain liability and strengthen the polluter pays principle (Bergkamp, 2020).

Liability regimes are primarily ex-post approaches, where the question of a technology's acceptable or unacceptable risk is considered after some harm has occurred. They install systems to compensate for damage. But the risk of liability has the ex-ante effect of incentivizing precaution. It can encourage deterrence, by providing incentives for people to behave optimally from a safety and risk perspective. However, judges can only act on the basis of someone launching a lawsuit, on a particular request. This limits the courts' ability to regulate emerging technologies. In a liability case, the judge will have to apply relatively open-ended and often very general standards, rather than detailed rules or concepts. This requires interpretation and application to specific situations.

The concept of sustainability from the perspective of a court is relatively vague. To apply it, the court will first have to engage with a higher level of interpretation than it is used to, and may not find the kind of relevant facts that it should consider to support its judgement. Then, would the court be authorised to apply these relatively vague concepts from a legal perspective, without having political authority (legitimacy)?

A more recent objective of liability regimes, especially in Europe and to a lower degree in the US, appears to be to oversee the regulatory process or risk assessment procedures, in particular to the extent they produce binding orders or decisions. The recent climate cases mentioned below are examples.

The role of the judiciary

Could the judiciary begin to set jurisprudence to require more mitigation or remediation of risks to environmental sustainability? What would be the legal basis? In 2021, several court cases showed the ability of the judiciary system to push governments to increase their actions towards climate change mitigation and to impose liability on the fossil fuel industry for causing climate change. In April 2021, Germany's Constitutional Court ruled that the 2019 *Climate Protection Act* was insufficient because it lacked details on emissions reduction beyond 2030 (Amelang, 2021; Appunn & Wettengel, 2021; Boldis & Lütkehaus, 2021). In February 2021, a French court ordered the government to make up for its failure to meet its own greenhouse gas reduction targets, saying it needed to "repair" the emissions overshoots (Reuters, 2021). In May 2021, Royal Dutch Shell Plc was ordered by a Dutch court to cut its emissions further and faster than planned (Baazil et al., 2021). The court found that Shell's existing carbon mitigation strategy was "not concrete and is full of conditions … that's not enough." This ruling could have far-reaching consequences for the rest of the global fossil fuel industry. It sets a precedent that corporations can be held liable for causing climate change. These verdicts could have implications for climate cases around the world and will be scrutinised globally amid a new era of litigation related to climate change.

It is worth wondering whether these cases could set precedents that NGOs could use to build cases around damages to the environment and environmental sustainability caused by private or public actors that make decisions or deploy plans towards sustainability, if it is shown that those actors do not deploy sufficient actions to meet their plans or that they contradict fundamental principles or rights.

Bonds and other forms of financial guarantees

Finally, and in connection with liability, anticipatory bonds may play a role for certain types of risks that might have long-term and large effects that are not yet identified when the activity leading to that risk is undertaken. These bonds or other forms of financial guarantees would be available in case a company is unable to pay for specific damage caused by the activity. Some people have argued for broader types of financial guarantees that could be required, for instance, in the context of engaging in very broadly defined types of activities, including emerging technologies. Although the framing would be difficult, such guarantees could also create preventive incentives to keep harm from arising, if structured the right way, possibly partly through insurance and partly through other means.

Sustainable finance, funding and grant-making

Investors and research-funding organisations, such as scientific institutions and grant-making foundations that provide funding and other forms of support to R&D, have a role to play. To what extent do they take into account second-order sustainability risk or potential unintended damage to the environment? Can they design criteria for selecting or encouraging technology development that will not, unintentionally, aggravate the state of the environment and the climate? At the same time, is greenwashing a cause for concern (The Economist, 2021)?

Chapter 5

Overarching recommendations

To what extent could environmental sustainability considerations be included early in the technology development process? As previously mentioned, many challenges would have to be addressed and barriers or obstacles overcome. Acknowledging the difficulty of capturing and making the concept of environmental sustainability concrete, and taking into account the features of emerging technologies in various fields, this chapter offers certain overarching interim recommendations, which would need to be refined in further work and perhaps adapted to specific emerging technology applications. Cutting across most of the recommendations is the need to engage more systematically with stakeholders from the public as well as practitioners, during research and implementation, to include a wide range of relevant knowledge and perspectives regarding the sustainability but also acceptability of emerging technologies. The following recommendations primarily result from the current or possible response strategies detailed in Chapter 4.

The refinement and implementation of all recommendations in this section will necessitate the collaboration of various actors, including in research, industry and regulation, so should, at this stage, be considered by all stakeholders involved in technology development. Greater refinement will be developed in further work.

↦ Systematise early-stage technology assessments

The development and use of concrete approaches and tools for early-stage technology assessments (TAs) should be systematic in institutions that advise policymakers in governments and parliaments on where and how to support or regulate specific technologies. Sustainability should not be prescribed or considered only after the technology has been deployed in actual products. It should be included in what early-stage TAs look for and described in their outcome, even if only indicatively.

Digital technologies, for example, may have such a profound impact on electricity consumption that their carbon footprint should systematically be estimated. They also have important knock-on effects on ecosystems that should be identified and described to the extent possible. Similarly, public decisions about the transport sector's electrification should be informed by early-stage TAs and include a review of plans for electricity and battery production and for recycling the batteries, as well as an examination of the broader impacts.

↦ Develop methods and tools for prospective life-cycle assessments

Collaborative research efforts should be encouraged to develop methods and standards for prospective life-cycle assessments (LCAs). These should systematically be used in the early development phases of a technology, when there is a lack of data and uncertainty about the future product and market, but there is still time to change the technology's design to establish fundamental conditions that would ensure the sustainability of the application or outcome.

For example, large-scale CDR techniques should not be deployed without prospective LCAs to capture the long-term impacts on broader ecosystems and the climate itself, and space technologies should be scrutinised for their impact on environmental sustainability in space.

↦ Refine and implement sustainability-by-design

In analogy with "safety-by-design" which aims to prevent a product from causing safety risks (or risk to human health), the concept of "sustainability-by-design" looks promising at first sight but is challenging in the details. Efforts should continue to develop frameworks and criteria in selected domains, which funding agencies, investors, industry leaders and regulators could consider to encourage technology with built-in sustainability. Criteria could include safety, resource use and circularity (recyclability), and the effects on greenhouse gas emissions and on ecosystems.

For example, implementing the EU Chemicals Strategy for Sustainability (EC, 2020b) is an opportunity to develop substitutes to hazardous chemicals and make progress towards circularity.

↦ Create a value proposition for sustainability

Environmental sustainability will only be achieved if a rewarding value proposition is developed, which identifies clear, measurable and demonstrable benefits for innovators and investors. A strong value proposition would help innovators to reconcile long-term sustainability and short-term innovation goals, and end-users to prioritise environmental sustainability in their choices. Government interventions that help to internalise both positive and negative externalities associated with sustainability can enhance the value proposition. Performance-based standards and certification also have a role to play.

For example, CDR approaches are generally costly, with benefits that accrue to global society more than to those who invest in concrete plans. Appropriate business models are yet to be built. Sustainable CDR will need an explicit price (like the dollar value on carbon emissions in carbon trading systems), which would help to address the incentivising challenge.

↦ Develop flexible and adaptable regulatory frameworks

To become more agile and responsible while continuing to provide certainty in basic regulatory frameworks, regulators are advised to adopt the principles of Planned Adaptive Regulation (PAR), an approach in which a regulation is designed from its initiation to learn from experience and to be revised over time. PAR requires planning for future review and revision of the governance arrangements; the funding of targeted research; the monitoring of the performance and impact of existing arrangements; and concrete review and revision to meet the predefined vision for environmental sustainability.

For example, regulatory frameworks for synthetic biology applications fluctuate between regulating products and processes, with limitations in both cases. Regulating applications based on their function as well as expected and actual outcomes in the environment and society, in a progressive manner, could make room for allowing beneficial or essential uses while avoiding actual and perceived risks that society is not willing to take, in view of the outcomes.

↦ Establish an environmental sustainability compass

Preliminary considerations for developing a compass to indicate the direction to environmental sustainability, which would be analogous to a GPS and map, include the following:

- Sustainability is foremost a question of **attitude**. It is necessary to evaluate if science and technology developers, industry leaders and investors have the relevant attitude towards environmental sustainability matters, and to encourage sustainability culture in technical science and engineering education.
- The sustainability of emerging technologies results from **policy** prescriptions and appropriate **regulatory** instruments. A sustainability compass could suggest pathways to reach a certain point and provide recommendations regarding approaches for sustainability assessment, and policy and legal requirements. An analogy could be the directions provided by Google maps, where users can indicate their preferences within the boundaries set by road safety rules.
- **Incentivising** sustainable innovators, developers and investors is essential. A compass could serve to provide or indicate available incentives that reward engaging in practices that lead to environmentally sustainable technology development, deployment and investment.
- Developing the compass requires **institutionalisation**. A compass should have a home and an owner responsible and rewarded for avoiding environmentally harmful technology choices and policy decisions.

Appendix 1

Technology domains

This appendix contains a selection of specific issues in the five technology domains discussed in the workshop, concerning the potential emergence of risk to environmental sustainability as a result of implementing emerging technology in new products or systems.

For each technology domain, background information and answers to questions discussed in breakout groups during the workshop are provided. Kyle Finley (chemicals), Jesse Reynolds (synthetic biology), Benjamin Trump (digital technologies), Rainer Sachs (carbon dioxide removal and sequestration) and Romain Buchs (space technologies) facilitated the group discussions and reported on the main outcomes, presented below.

1.

Chemicals: Advanced materials and smart nanomaterials

Background information

The chemical industry contributes to improving performance in a large array of industrial processes and products. However, as in other sectors, concerns have been raised about risks posed to the environment. Potential adverse effects may not be adequately assessed in certain areas, such as when the effect is delayed or cannot be tested in labs or closed environments, potentially leading to environmental damage that may manifest only in the open environment and in the longer term.

The current interest in improving the environmental sustainability of chemicals is demonstrated in the US and Europe by such important policy initiatives as the *US Sustainable Chemistry Research and Development Act* (Bergeson & Campbell, P.C., 2021; Hogue, 2021) and the *EU Chemicals Strategy for Sustainability* (EC, 2020d), European Green Deal (EC, 2019) and *Circular Economy Action Plan* (EC, 2020a).

Sustainability aspects generally focus on hazardous properties, the mobility of a substance, greenhouse gas emissions, resource consumption and responsibility in the supply chains (Umweltbundesamt, 2016).

Incorporating sustainability aspects in the development of chemicals, for example through the use of safe and sustainable-by-design (SSbD) criteria, is a prerequisite for a sustainable circular economy. While safety-by-design has been a requirement in many domains for some time already, adding sustainability aims to take into account the UN SDGs and extend the concept so that it can be applied to increasingly complex and advanced materials. Several research programmes and policy institutions in Europe are working to develop and implement a systematic and comprehensive strategy to consider sustainability very early in the development of new materials and products (see, e.g., SweNanoSafe, 2021). Key factors include the reuse of materials and products in a circular economy.

To illustrate the challenges to ensure the environmental sustainability of chemicals, briefly detailed below are issues associated with three products developed by the chemical industry: batteries for electric vehicles, plastics and smart nanomaterials.

Batteries for electric vehicles

Some industry analysts predict that at least 145 million electric vehicles (EV) will be on the road by 2030, up from just 11 million in 2020 (Morse, 2021). How will the millions of EV batteries that manufacturers expect to produce in the coming decades be recycled? Are EV batteries really designed to be recycled? Will they actually be recycled safely and sustainably? While there is much uncertainty at the global level, the proposed EU COM(2020)798 legislation (EC, 2020c) makes such plans for new battery legislation prioritising the development of a complete value chain to recycle batteries for a second life, thus supporting circularity as per the European Green Deal for sustainable batteries (EC, 2020b). After their first life in cars, batteries would be used to store energy on the grid, thus adding capacity for the storage of renewable energy and shavings peaks on electricity demand for electric cars.

Plastics

Given the significant concerns about damage caused by plastic pollution, and despite the difficulty in changing industrial practices and consumer behaviour (Yosie, 2021a), scientists and technology developers are working hard to develop regulatory and technical solutions to prevent and remove plastic pollution (Nicholas Institute for Environmental Policy Solutions, 2020; Schmaltz et al., 2020). Examples include preventing untreated wastewater from entering the environment in the first place and recycling the plastic by breaking it down into basic molecules (Nikiema et al., 2020).

Is there a risk that in the rush to find solutions, the proposed resolutions will be implemented before they are sufficiently vetted against adverse effects that would manifest much later? For example:

- To what extent is biodegradable plastic possible and a sustainable solution?
- How are clean-up technologies for micro-plastics in the marine environment evaluated (see, e.g., InNoPlastic, n.d.)?
- Is the use of enzymes to recycle PET a good idea (Crownhart, 2021; Service, 2020)? Are all the possible effects well known? Or is there a risk that the cure is worse than the disease?

Smart nanomaterials

Smart materials (also called active, adaptive or stimuli-responsive materials) quickly and reversibly change certain critical properties during use. There are many expected opportunities for smart nanomaterials (SNMs) in medicine, cosmetics, food, food packaging, electronics, environmental safety (gas detection, contamination remediation) and agriculture. Novel or enhanced properties improve performance over conventional products and processes. For example, when SNMs are used in sensors or targeted delivery systems, specific functions are activated upon exposure to one or more external stimuli (Gottardo et al., 2021). In 2019, the European Chemicals Agency (ECHA) identified 48 nano-enabled products in the second generation (active nanomaterials, nanostructures and nanostructured materials) and eight in the third generation (multifunctional nanosystems), with about 70% of them already on the market (see Camboni et al., 2019, and definitions therein). The majority are for medical applications, and about a quarter are for electronics (Gottardo et al., 2021).

Because of their changing properties, however, SNMs pose crucial challenges to risk assessors who cannot predict with sufficient certainty the behaviour of the materials and their possible toxicological effects after release into the environment and throughout their life cycle. Therefore, and depending on the application domain, risk assessment is often insufficient to meet regulatory requirements for safety and expectations on long-term environmental sustainability. The need to consider the sustainability of nanoscale materials is not new (Bergeson, 2013). It has always been challenging in practice, with difficulty to perform risk–benefit analyses encompassing the full life cycle and a lack of methodological tools to get a systemic view (Möller et al., 2012). Regarding SNMs in particular, the challenges raise the following questions:

- What kind of tools could help assess the long-term environmental sustainability of SNMs?
- How can sustainability-by-design be implemented?
- How can the circular economy concept be translated into incentives, instruments and regulations?
- Would a precautionary approach be advised for SNMs? How can innovation and precaution be balanced to ensure environmental sustainability (Gazsó & Pavlicek, 2020)?

Outcome of workshop discussions

How would you describe the approach taken in the field to discuss (or not) the question of emerging technologies' environmental sustainability, and in particular the approach to:

- **Think (or not) in terms of the need to ensure that the outcome of an emerging technology (or its applications) does not cause damage to long-term environmental sustainability**
  It would be unrealistic to expect that developers of an emerging chemical technology should be responsible for ensuring a sustainable outcome, whatever application from that technology is developed. However, technology developers should design their technology so that its applications can be sustainable. Part of the challenge is that tools are missing at the technology's early stage of development and, at later stages, developers are primarily interested in neatly-bounded attributional LCAs. However, policymakers should require assessments, such as prospective LCAs, that are extended to include system-wide impacts. The relatively new concept of sustainability-by-design is not mature enough to be implemented in standards and regulations.

- **Work to identify possible threats (foresight), conduct early-stage technology assessments and prospective LCAs**
  One of the aspects that makes the assessment of chemicals difficult, especially when it comes to nanomaterials or advanced materials, is that some of the environmental or biological impacts may not be seen for years after products are deployed. One potential method to limit unintended damage from new chemical products or technologies is assessing them for their entire life cycle. Chemical process safety methodologies already use life-cycle approaches. Much focus is placed on waste management or product liability, but attention also needs to be paid to the more immediate, mundane concerns of energy consumption or similar impacts.

- **Develop suitable technical instruments and governance mechanisms to enable, for example, sustainability-by-design**
  Sustainability-by-design (SbD) is a laudable goal but important challenges must be overcome to translate the concept into operational methodologies. The absence of assessment tools leads to a lack of data and missing knowledge. However, important work in the EU aims to define a framework and criteria for SbD.

- **Balance short-term expected benefits and long-term possible costs**
  In the example of battery electric vehicles, which are being developed to address an immediate concern (the need to reduce CO_2 emissions), long-term indirect adverse consequences (e.g., mineral extraction, challenges related to battery recycling) are drawing increasing attention. These matters would need to be considered upfront in comprehensive life-cycle analyses. The current wait-and-see attitude ignores the long-term consequences of technical solutions that appear good at first sight but that should be scrutinised and monitored to react and change the course of action if needed.

- **Differentiate ethical concerns from environmental concerns**
  Some moral/ethical guidance is needed in research and industry when there is no regulatory requirement or internal code of conduct for selecting and using certain materials. But ethical and social concerns are not mainstream in the chemical industry, aside from evaluating the industry's contribution to the global economy and welfare.

- **Educate researchers, technologists and investors (industry and finance)**
  Three groups should be targeted in particular: students, researchers, technology developers; producers and manufacturers; and consumers.

Is there cause to worry today about the indirect environmental concerns possibly associated with emerging technologies? Which specific risks, applications or prospective products require further study?
In the case of advanced materials or convergent technologies that combine various distinct technologies, often with active or adaptive properties that change in responses to stimuli, anticipating the full extent of the direct and indirect consequences is very difficult. The instruments and methods available for assessing the products resulting from these technologies are insufficient to identify and characterise the effects outside of intended context or use. Moreover, the instruments for emerging technologies' early-stage assessment are not able to capture the uncertain and dynamic nature of their production.

How can decision-makers include the consideration of long-term adverse environmental impacts in their decisions?
The industry routinely applies the principles of effectiveness, performance, cost-efficiency and safety. It usually prioritises what is close to it: customers (consumer preferences) and employees (workers' safety). Overall, it is usually focused on business goals and regulatory compliance and, to some extent, sustainable development, primarily when linked to market opportunities.
Individual chemical products are part of long and complex supply chains, and performing evaluations at every stage of the chain is difficult, if not impossible. It can be easy for companies to push issues elsewhere in the supply chain. This is a challenge for regulators: how far can those reasonably go? Can responsibility for end-product environmental sustainability be established? Is it more promising to enhance consumer awareness and affect their preferences?

Where are new approaches and instruments most needed, or which instruments should be improved?

- New approaches are needed to assess and manage safety and sustainability across supply chains. Most of the attention is currently placed on products and processes, with less on systems. Regarding products, risk assessors and managers use concepts and instruments to evaluate and develop safety, containment, exposure and "control." Regarding systems, relevant concepts (and therefore instruments) include supply chains, circularity, risk–benefit trade-offs, risk–risk trade-offs, processes, resilience, etc. For example, the *EU Chemicals Strategy for Sustainability* (EC, 2020d) requests the implementation of SSbD, but most current efforts continue to target products (as per a name search and count in 2020 and 2021 EU policy documents), not the supply chain or the system in which the product is produced, consumed, recycled and perhaps reused.
- **Although not without challenges, safety assessments can be expanded to sustainability assessments.** Because the chemical industry is familiar with the concept of safety, it would seem logical to consider environmental safety as a precursor of environmental sustainability and thus to expand from safety assessments to sustainability assessments. But, whereas safety goals gradually move towards zero risk, sustainability is a moving target that cannot be set once and for all. Instead, it requires a dynamic systems approach and the re-evaluation of assessments as systems change over time in response to internal and external drivers and stressors. The sustainability of products or processes derived from emerging chemical-based technology would result, for example, from a set of properties of the system that would not consume more than it can produce or renew.
- **Regulation of the emerging chemical industry can be made more agile and adaptive.** The effectiveness and cost-efficiency of regulations could be improved with periodic reviews and the integration of feedback from monitoring the outcomes of existing regulations on safety and sustainability. Companies would provide updated information to regulators. Regulators would encourage the gathering, processing and sharing of data. Altogether, this would allow the earlier identification of new potential issues and regulatory improvement. The concept of regulatory preparedness (Jantunen et al., 2018), in which regulators prepare themselves for new products from research, is promising to help address the pacing problem (i.e., that regulation is delayed, slowing the introduction of promising innovation to the market).

2.

Synthetic biology: Gene editing and gene drives

Background information

In 2019, the International Union for Conservation of Nature (IUCN) noted in the introduction to its assessment of the impacts of synthetic biology on conservation that "[s]ynthetic biology — altering or redesigning genes to meet human objectives — is a fast-developing field with significant potential impacts on nature conservation" and that it "could have substantial knock-on effects on conservation — including modified genes spreading to non-target species and affecting broader ecosystems, but also benefits such as saving threatened species, reduced fertiliser use or diminished demand for products derived from threatened species" (IUCN, 2019; Redford et al., 2019).

A briefing from the European Environment Agency (EEA) about synthetic biology and the environment questions the impact of applying engineering principles to biology: will it result in "new approaches to biodiversity conservation, or unexpected but irreversible forms of environmental disruption?" The briefing notes, "some scientists have warned that such technologies represent 'a new stage and depth of the power and intervention into ecosystems', potentially driving 'these ecosystems beyond their tipping points'. Unintended changes could be irreversible. Such applications of synthetic biology raise a variety of concerns" (EEA, 2020).

Risks to environmental sustainability could be particularly striking with gene drives — "genetic elements that skew the patterns of inheritance, thereby accelerating the spread of a given characteristic" (Deplazes-Zemp et al., 2020). Oye et al. (2014) suggest several steps towards managing environmental risks. A recent case study on the governance of gene drives is provided in Millet et al. (2022), who state that "gene drives deserve special attention because of their potential for widescale impact and remaining uncertainty about how to evaluate intergenerational and transboundary risks."

A brief look at these risks and the challenges of conducting environmental risk assessments, an integral part of the EU's regulatory approval procedure, follows.

Gene drives

A Swiss Academies Factsheet (Deplazes-Zemp et al., 2020) about the benefits, risks and possible applications of gene drives notes that one of the most striking features of gene drives is their "self-propagating nature", which "poses specific risks, including:

- Increased challenges in containment over conventional genetically modified organisms (GMOs). This is a possible risk if gene drive organisms escape unintentionally into the environment and breed with local individuals during the research and development phase;
- Difficulties in preventing gene drive organisms from spreading into non-target populations of the same species and sexually compatible (sub-)species;
- The risk that gene drives are difficult and perhaps impossible to stop if unexpected effects are observed during the application phase;
- The potential to spread across national borders, which could result in international regulatory incidents."

As reported in the Factsheet: "As with other interventions and technologies, there exist more general risks that are currently being discussed. These include potential negative ecological effects that are hard to predict due to the complexity of the systems and the potential for misuse" (Deplazes-Zemp et al., 2020). A workshop funded by the US National Science Foundation explored the potential ecological effects of gene drives, their complexities and the intersection of risk analysis, sustainability and ethical issues through systems mapping, highlighting important risk governance aspects and research needs (Kuzma et al., 2018).

The Factsheet also notes ethical considerations: "The idea of humans redesigning both the genome of organisms and its patterns of inheritance – with potentially irreversible consequences – may be seen by many as a particularly profound and ethically problematic interference with nature (e.g., explored in the context of synthetic biology). For others, the use of gene drives may be perceived as a continuation of the technological activities of human societies since the dawn of agriculture. Most ethical questions relate more directly to the balance of risks and benefits as well as their fair distribution amongst the stakeholders involved" (Deplazes-Zemp et al., 2020).

Environmental risk assessment

Dolezel et al. (2020) argue that “it remains unclear whether the relevant regulatory provisions will be fit for purpose to cover [the gene drive organisms’ (GDOs)] potential environmental, human and animal health risks if environmental releases of GDOs are envisaged.” Regarding the potential applications of gene drive systems in public health (e.g., vector control of human pathogens), agriculture (e.g., control of weeds or pests) and environmental protection and nature conservation (e.g., for the control of non-native species), the authors note that “the assessment of [...] potential risks to the environment and human and animal health will be of high importance if these [gene drive] organisms are to be deliberately released into the environment” (Dolezel et al., 2020). Concerns have arisen also about the lack of clarity regarding responsibility for the efficacy and sustainability of health interventions.

Dolezel et al. (2020) list the following challenges of gene drives for the environmental risk assessment (ERA) in the EU:

1. The receiving environment cannot be defined for GDOs with the ability to spread globally.
2. The safety of a GDO cannot be established based on a comparative assessment.
3. The environmental impact of gene flow of GDOs cannot be assessed with the current ERA.
4. Testing of GDOs in the field is hardly possible.
5. Long-term risks at the population and ecosystem level cannot be assessed with current ERA methods.
6. Improved environmental monitoring and risk management must be operational before deploying GDOs.

Kuzma et al. (2018) and Kuzma (2021) previously identified similar challenges for environmental risk assessments of gene drive organisms. Because the assessment of gene drives will be difficult prior to release given the uncertainties, Kuzma (2021) proposes a model for risk analysis focusing on procedural validity drawing on the IRGC (2015) guidelines for governance for emerging technologies and principles of responsible research and innovation like anticipation, responsivity, reflexivity and inclusion.

Outcome of workshop discussions

How would you describe the approach taken in the field to discuss (or not) the question of emerging technologies’ environmental sustainability, and in particular the approach to:

- **Think (or not) in terms of the need to ensure that the outcome of an emerging technology (or its applications) does not cause damage to long-term environmental sustainability**
  Within the scope of synthetic biology, the intentional use of advanced biotechnology techniques in outdoor in situ environments (i.e., not agriculture) is a matter for discussion. The synthetic biology field devotes substantial attention to the risks of negative impacts to the natural environment and how to avoid them. Importantly, the focus is on the long-term effects to sustainability, but also on other impacts on society, ethics and the economy. In fact, some workshop participants asserted that the scholarship and governance discourse concentrates too much on precaution and minimising risks.

- **Work to identify possible threats (foresight), conduct early-stage technology assessments and prospective LCAs**
  According to the scholarly literature, the means to identify synthetic biology’s possible threats to long-term environmental sustainability are numerous. These include multi-criteria mapping, expert elicitation, responsible research and innovation, and anticipation.

- **Develop suitable technical instruments and governance mechanisms to enable, for example, sustainability-by-design**
  Gene drives and other forms of synthetic biology may be technically designed to reduce potential long-term damage to environmental sustainability through, for example, threshold, daisy, reversible and rescue drives, and gene drives that depend on genetic characteristics found only in the targeted population.

- **Balance short-term expected benefits and long-term possible costs**
  Synthetic biology, as meant here, is not a typical emerging technology in which a private actor captures short-term benefits while the public bears the long-term costs. Instead, techniques are being developed largely for purposes related to public goods, such as eradicating infectious diseases and invasive species. Both the benefits and costs are

commonly framed as long term. A central difficulty of long-term planning is that values can change over time. The fact that past regulators and other decision-makers did not seek (to avoid) what the current ones seek (to avoid) does not necessarily mean that those in the past thought only in the short term.

- **Differentiate ethical concerns from environmental concerns**
  Ethical and environmental concerns cannot or should not be separated. But the same can be said for ethical and economic concerns. One strong argument suggests that the task of governance is to steer decisions towards widely agreed-upon objectives, yet some ethical norms remain contested. An asymmetry may subsist between existing and proposed activities, and between acts of commission and omission. It is unclear whether this asymmetry is ethically defensible.

- **Educate researchers, technologists and investors (industry and finance)**
  Education was not a significant topic of discussion during the workshop.

Is there cause to worry today about the indirect environmental concerns possibly associated with emerging technologies for gene editing and gene drives? Which specific risks, applications or prospective products require further study?
Opinions differ with respect to appropriate governance responses, but the general agreement appears to be that gene drives pose significant risks to environmental sustainability. The challenge here is defining environmental harm or risk and characterising it. Different people will consider it to include and exclude various impacts. This is especially true when thinking long term, as values change, and related to potential impacts that are more systemic or holistic in nature.

How can decision-makers include the consideration of long-term adverse environmental impacts in their decisions?
As noted above, the literature covers numerous means to identify synthetic biology's possible threats to long-term environmental sustainability. However, they are rarely used as bases for regulation. This may be due to insufficient political will, to influential producers' interests and to a dominant capitalist ethos. But integrating long-term risks into governance is challenging, as the risks are second (and higher) order and are difficult to delineate, assess and attribute ex-post.

Where are new approaches and instruments most needed to account for long-term impacts or the improvement of current instruments?
Specific governance mechanisms are difficult to identify, but certain suggestions are proposed:

- The Millennium Ecosystem Assessment offers a framework for considering the multiple dimensions of human impact on sustainability, not just on the environment.[10]
- A technology-wide environmental impact assessment could be required prior to the deployment of an emerging technology application.
- Liability for harm may be an underused governance mechanism, as this could align private and public incentives.

Even those who disagree about the urgency and ideal stringency of additional synthetic biology regulation seem to agree on the following challenges:

- Existing rules were designed for the technologies, risks and values at the time the rules were drafted. New technologies are typically partially governed by these legacy regulations, but this governance is often suboptimal. The rules' existence reduces the political will to update them or develop new ones. Furthermore, developing new regulations for each (seemingly) novel technology would multiply the rules, potentially causing burdensome complexity and inconsistency.
- A widely perceived challenge is to identify an appropriate baseline for comparison. Emerging technologies, such as synthetic biology, are usually not merely added to some system, but (at least partially) replace a system's existing components. An example is crops genetically modified to contain pesticides. Should their environmental risks be compared with those of unmodified crops, or with those of unmodified crops plus those of the typically accompanying chemical pesticides?
- Another challenge is that gene drives — the highest-leverage synthetic biology technology — are under greatest consideration in sub-Saharan Africa, where institutions are often weak. In these circumstances, even well-designed governance is often not well implemented.

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[10] Information on the Millennium Ecosystem Assessment is available at millenniumassessment.org.

3.

Digital technologies: Machine learning, cloud computing and blockchain

Background information

The rise of information and communication technology (ICT) has led to profound changes in the way goods and services are produced and consumed. ICT is ubiquitous in our societies; it includes consumer devices, networking technologies and data centres, which comprise both hardware and software.

Questions are starting to be raised about specific ICTs and their applications' impact on societal equity and, to some extent, on environmental sustainability. Although digitalisation (i.e., the application of ICT throughout the economy and society) is often seen as a way to reduce energy demand and carbon emissions (e.g,. Deloitte MCS Limited, 2019; Mickoleit, 2010) and improve environmental sustainability (e.g., sensors and IoT for environmental monitoring; Ullo & Sinha, 2020), it has a growing environmental impact, notably huge electricity consumption (see Figure 6).

In the ICT sector, matters of long-term environmental sustainability are not currently a major focus of attention. Instead, the focus is on social aspects and societal, institutional and political transformations that would unfold with the large-scale deployment of

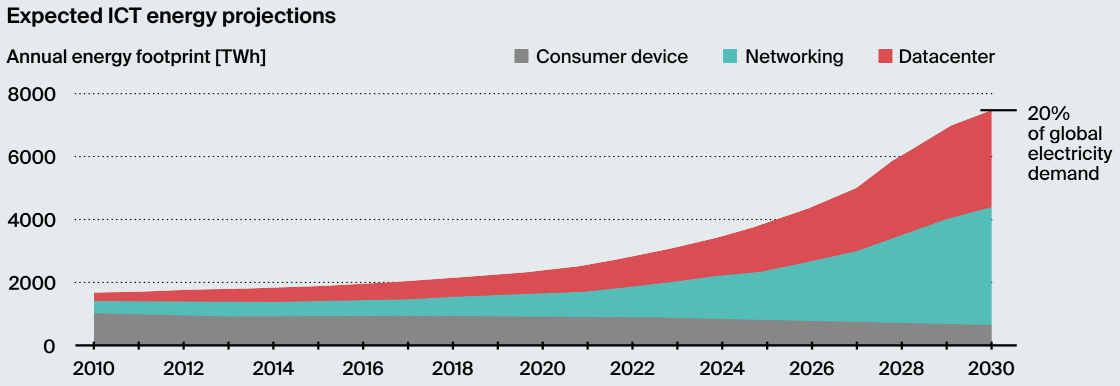

Figure 6 | Projected growth of global energy consumption by ICT (data from Andrae & Edler, 2015; adapted from Gupta et al., 2021)

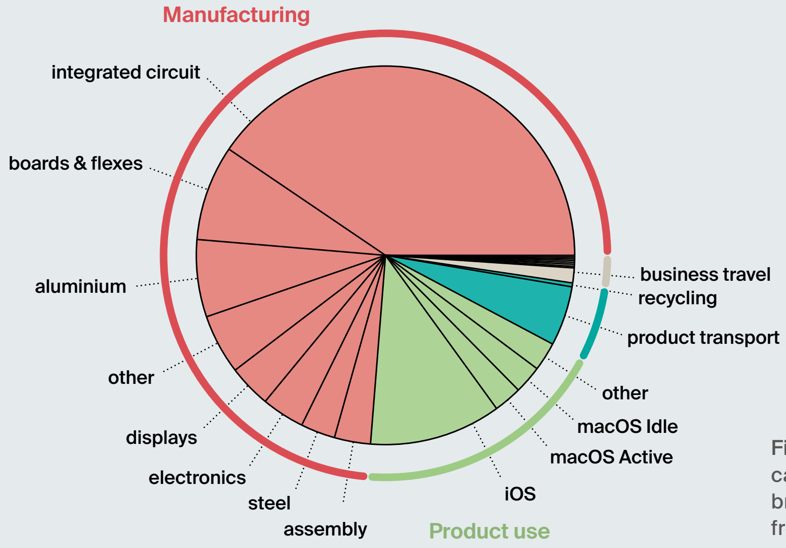

Figure 7 | Apple's carbon-emission breakdown (adapted from Gupta et al., 2021) emerging ICTs, such as algorithmic decision-making and cryptocurrencies, and concerns about ethics, privacy, accountability, fairness and the protection of civil rights.

When discussing the environmental impact of digital technologies, much of the attention today focuses on current and projected electricity consumption and, in some cases, how the electricity is sourced (nuclear, fossil, renewables). However, digitalisation is also linked to various other adverse and complex impacts on the environment through the consumption of water and materials (natural resources, such as aluminium, lithium, cobalt) and the generation of waste.

Advancements in energy efficiency and higher renewable energy penetration have reduced the carbon emissions produced by hardware use. Now, most carbon emissions come from infrastructure construction and manufacturing. For example, manufacturing totals 74% of Apple's carbon emissions, while product use accounts for only 19% of the company's emissions (see Figure 7 and Gupta et al., 2021).

Threats to the long-term environmental sustainability of ICT

Energy consumption, however, is not the only factor in unintended adverse consequences to the sustainability of the natural environment and climate, which are currently ignored (unknown) or neglected (purposely). Other factors include fossil and natural resource consumption (overuse, mining, etc.) and waste disposal, recycling and reuse. These three elements can lead to greenhouse gas emissions and unsustainable resource use, and negatively affect ecosystems and biodiversity, possibly for the very long term and sometimes with irreversible consequences on biodiversity and ecosystems. Non-energy related environmental pressures include:

- **Direct impacts on resources**. "The mining and extraction of raw materials (e.g., cobalt, palladium, tantalum, silver, gold, indium, copper, lithium and magnesium) as well as the production of microelectronic components, especially integrated circuits, are the main contributors to fossil resource depletion as well as abiotic resource depletion, global warming, freshwater eutrophication, soil acidification, human toxicity, freshwater toxicity, marine toxicity, and terrestrial toxicity" (Liu et al., 2019).
- **Direct impacts on biodiversity and land use as well as land-use change**. "The assessment of related impacts of ICT is challenging, as the cause-impact relationships are very heterogeneous and indirect. [...] Major impacts result from the extraction of natural resources needed for the production of hardware, from the release of hazardous materials [...] related to raw material extraction processes, as well as from the inappropriate collection, recycling and disposal waste of electrical and electronic equipment. Environmental impacts of power generation (e.g., greenhouse gas emissions) can also include biodiversity impacts" (Liu et al., 2019).
- **Other indirect and systemic impacts on the environment**.

Cloud computing and data centres

Data centres account for about 1% of global electricity demand (IEA, 2020). This energy demand could remain flat in the coming years, as the strong growth in demand for data centres can be offset by efficiency improvements and a shift to a greater share of cloud and hyperscale data centres (IEA, 2020). As data centres increasingly rely on renewable energy, carbon emissions originate to a greater extent from supply chain emissions than from direct emissions from facility use. As a result, construction, infrastructure and hardware manufacturing are becoming the dominant parts of data centres' emissions.

Machine learning

Advances in techniques and hardware to train machine learning (ML) algorithms have led to significant accuracy improvements. These advancements, however, require important resources, both in hardware and energy, giving rise to high environmental costs. For example, Facebook increased its hardware devoted to ML training and inference by about four times in less than two years (Gupta et al., 2021). In addition, the training of deep learning models for natural language processing requires a vast amount of energy and their tuning requires even more (Strubell et al., 2020).

The ML research community has been focused on developing more accurate models without much attention to their efficiency (Schwartz et al., 2019). Performing a cost–benefit (energy-accuracy) analysis of the methods would help to prioritise the most efficient ones. To do so, Strubell et al. (2020) suggest that "authors should report training time and sensitivity to hyperparameters" to enable comparisons across models. Efforts have been undertaken to develop metrics that balance accuracy, complexity and carbon footprint to select better models (Lenherr et al., 2021, propose the recognition and training efficiency to compare deep learning models and platforms). Various tools have been developed to increase transparency regarding the carbon footprint of ML algorithms and help developers take this aspect into account (Anthony et al., 2020; Henderson et al., 2020; Lacoste et al., 2019).

Blockchain systems

Blockchain systems (and, more widely, distributed ledger technology) are a new paradigm to share information with numerous applications. They could contribute to the SDGs by, for example, supporting the realisation of sustainable and trusted supply chains, improving energy efficiency, and promoting the creation of secure and reliable smart cities (Parmentola et al., 2021). However, some of this technology's large-scale applications come at an environmental cost due to the significant energy required. One blockchain application, cryptocurrencies, has been the focal point of environmental sustainability concerns. Bitcoin, the cryptocurrency with the largest market capitalisation, consumes an enormous amount of energy (about the same as the Netherlands), with approximately two-thirds of it coming from fossil fuels (Rowlatt, 2021). The exact energy use is unknown, as cryptocurrencies are by design hard to track. Still, the consensus is that Bitcoin mining is a very energy-intensive activity, and its overall contribution to societal goals should also be evaluated considering environmental factors.

Outcome of workshop discussions

How would you describe the approach taken in the field to discuss (or not) the question of emerging technologies' environmental sustainability, and in particular the approach to:

- **Think (or not) in terms of the need to ensure that the outcome of an emerging technology (or its applications) does not cause damage to long-term environmental sustainability**
  Environmental sustainability is a necessary goal for digital technologies and a multitier challenge, from upstream infrastructure and manufacturing pipelines down to individual consumers and companies. Overall, the field is generally aware of the environmental sustainability challenges associated with digital technology production (hardware and software, devices and infrastructure) and use. However, the field is less certain about the precise magnitude of the problem due to the paucity of data, making it difficult to communicate the environmental sustainability concerns to consumers, stakeholders and the lay public.
  The coarse characterisation of the problem coupled with insufficient data may be preventing sustainable decision-making for the digital infrastructure supply chain. For example, tracking carbon emissions from graphics processing unit (GPU)[11] usage in ML activities is not necessarily obvious to users and not easy to track in the aggregate for most countries. A necessary step is to move towards sustainability-by-design by addressing the massive gap in emissions and resource extraction data, and then packaging this gap in an understandable way for consumers. The IT industry could do the same as many airlines that can estimate ex-ante the emissions output for a passenger or shipped item. By learning such information, customers might be nudged to make more environmentally sustainable choices.
  The bulk of the sustainability challenge for digital technologies rests within broader infrastructure and manufacturing pipelines. Particularly for emissions, broader infrastructural characteristics, such as how energy is generated (e.g., renewable sources, fossil fuels), influence downstream environmental sustainability issues for energy consumers. If these upstream factors are adequately addressed, many environmental

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[11] GPUs are specialised electronic circuits designed for parallel computing, used for graphics and video rendering, and increasingly for ML applications

sustainability concerns within data centres, ML activities and even blockchain can be substantially ameliorated.

- **Work to identify possible threats (foresight), conduct early-stage technology assessments and prospective LCAs**
  Life-cycle assessments (LCAs) can help to address environmental sustainability challenges associated with digital technologies. Nevertheless, several core challenges remain. First, there are very few repositories where resource consumption and emissions data are hosted and made available for analysis by country or industry. Second, the environmental sustainability challenges would make any LCA relatively complex – emissions, resource extraction and consumption, and recycling have unique and recursive effects on the local and global environment.

- **Develop suitable technical instruments and governance mechanisms to enable, for example, sustainability-by-design**
  Sustainability-by-design (SbD) is a desirable goal, but the instruments and approaches to achieve it are not immediately clear or universal. A "commons" issue that must be rectified to achieve this goal is how environmentally sustainable practices can become the benchmarked preference for individual actors and overcome the influence of other possible counter incentives (financial, security, commercial).
  A way to achieve SbD is to create a competitive marketplace where environmentally sustainable practices can socially and economically outcompete environmentally unsustainable practices (notably, such competition occurs at the international rather than national level, so individual country restrictions would not sufficiently address this problem). Upstream solutions, such as increased robustness and greater efficiency of green energy supply, may address many emissions challenges. At the same time, improved practices at recycling scarce minerals and metals will reduce resource extraction costs. Infrastructure and products that limit or even reduce emissions and mineral extraction should be encouraged but alone will not address the systemic challenges of energy consumption that are the critical environmental stressor for digital technologies.
  The mandatory governance mechanism to enable SbD should first begin by requiring data collection and analysis of emissions and resource consumption for various digital technologies. While independent regulation or law may be necessary to govern individual components of digital technology applications, adapting existing international norms and codes of conduct might be more feasible to create a standardised baseline. Upstream, some international governance might be necessary (e.g., emissions tracking, metal and mineral extraction and consumption). Downstream, improving best practices to spur or inspire innovation within environmentally costly practices (e.g., energy-intensive GPU usage for ML and blockchain) can help to discontinue more environmentally costly practices and even commercialise sustainable alternatives.

- **Balance short-term expected benefits and long-term possible costs**
  The short-term benefits are currently prioritised over the burden of possible long-term costs. Like in many other domains, short- and long-term negative externalities are not internalised in the calculation of actual costs. Limiting offshoring, outsourcing and forum shopping through sustainable practices may influence individual actors to optimise in-house efforts and prevent the risk transfer of digital technology emissions overseas. However, until the various countries and industries become better acquainted with the issue and collect the necessary data, the typical stakeholder or consumer will be uninformed of the long-term costs. Short-term wins can drive sustainable practices through upstream (manufacturing pipeline and infrastructural improvement) opportunities, alleviating costs while sustaining technological benefits.

- **Differentiate ethical concerns from environmental concerns**
  In the context of ML, large data centres and blockchain, the increasing consumption of energy and materials for the benefit of a relatively small subset of society is a matter of ethical concern. If the costs of IT are increased through the internalisation of environmental cost, this ethical concern may worsen.

- **Educate researchers, technologists and investors (industry and finance)**
  The main challenge is a lack of data, which causes difficulty in comparing and communicating environmental sustainability challenges that individual digital technologies and industries may face. Addressing this issue and fostering clear, relatively jargon-free language and benchmarks for sustainable and non-sustainable practices are critically important. Otherwise, various industries

or countries will use incongruous approaches that allow the “commons” problem to linger.

Is there cause to worry today about the indirect environmental concerns possibly associated with emerging technologies related to digital technology applications? Which specific risks, applications or prospective products require further study?

It is worth addressing SbD challenges for digital technologies today due to the incremental and evolutionary nature of the technology (actions taken today may lead to a cascade of technological shifts in the coming years, which may be more or less environmentally friendly, depending on whether and how society intervenes).

While both emissions and resource extraction serve as the “risk objects” worthy of additional study, they must be discussed within the context of upstream and downstream applications. For upstream, it is critical to understand how improvements to major infrastructure and manufacturing capabilities can reduce emissions and improve resource recycling capabilities for companies and individuals. Downstream, it is necessary to understand how incentives or social nudges might push stakeholders to seek environmentally friendly improvements or behaviours with respect to digital technologies, including improving how environmental risk is analysed and communicated.

For specific applications and products, environmental concerns all bear common roots — increasing requirements of computing power (data centres, ML, blockchain, etc.). This includes emissions and resource consumption to manufacture computing units and electricity consumption when using them. As such, addressing one will likely have benefits in addressing others.

How can decision-makers include the consideration of long-term adverse environmental impacts in their decisions?

While preliminary steps exist, environmental impacts must be evaluated against the socio-economic benefits of various activities. A collective cost–benefit assessment, inclusive of an LCA, will allow policymakers and stakeholders to identify incentives, nudges or other opportunities to address the commons problem and foster a competitive demand for environmentally sustainable digital technologies. These advancements can allow quantifying the environmental impact that each of these industries may have. Only then is it possible to begin to make inferences about long-term sustainability challenges – for resource extraction, this includes the rate of depletion of critical metals and minerals, while, for emissions, this includes the rate of accumulation of pollutants locally and globally. Connecting such outcomes to (i) socio-economic impact (e.g., how environmentally unsustainable practices will disrupt jobs or economic activity), and (ii) health (e.g., how such practices will lead to morbidity and mortality) help to focus risk communication.

Where are new approaches and instruments most needed to account for long-term impacts?

For digital technologies, an LCA is critical both for material extraction and recycling, as well as emissions. LCAs should be standardised and benchmarked. They should enable broader assessment (not just a direct risk assessment), with rates of use of computing assets based upon their electricity requirements and the broader environmental costs.

For management, while regulations and laws might be necessary in certain contexts, it may be more productive to start with best practice guidelines that will be more effective in encouraging and nudging certain activities and behaviours (codes of conduct can prepare binding regulations). Any solution must fundamentally be coordinated at the international level, because national or regional policies will likely not address the underlying commons problem.

In addition to guidelines, bottom-up approaches in the form of standards and certification for computing efficiency (both while idle and under heavy use) can reduce electricity costs and thereby emissions and resource requirements. Efficiency enhancements will happen naturally as technologies improve but can be stimulated through local mandates.

4.

Carbon dioxide removal and sequestration

Background information

To achieve climate goals such as those of the Paris Agreement, and in addition to intensifying emissions reductions, massive decarbonisation of the energy system and large efforts to reduce the atmospheric concentration of greenhouse gases (GHG) through CDR are needed. This will require removing an enormous amount of GHG from the atmosphere and storing it safely, probably as permanently as possible (e.g., Florin, 2021; NASEM, 2019). Thus, a large carbon removal industry must be built in less than 30 years to remove about 10 Gt of GHG each year. This is 1 million times more than currently, representing a compound annual growth rate of almost 60% (Repmann et al., 2021).

Tensions exist between, on the one hand, the need to deploy CDR on a large scale as soon as possible (also considering the uncertainties about the potentials of the respective approaches) and, on the other hand, the identified or potential negative side effects and their associated uncertainties. The concept of essentiality, briefly discussed in Chapter 3, might be appropriate in this case and serve to increase the level of acceptable risk. Conditions would include the global consensus that the technology is needed; the effects and consequences are sufficiently known and understood by the populations; and society is willing to accept the risks in view of proven benefits.

The manifestations of adverse consequences will be very diverse, and most will be delayed. The balancing of benefits and risks thus depends on many factors and is very complex.

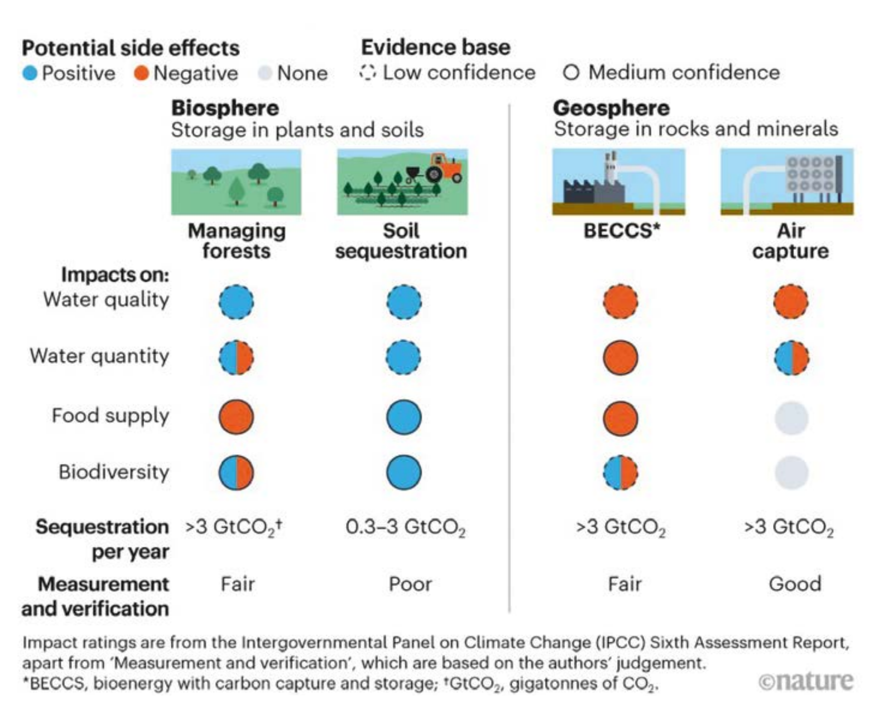
Main methods and environmental concerns

Approaches to remove carbon are usually grouped as follows (Rouse, 2020):

- **Nature-based approaches** seek to exploit natural systems capacities to absorb and store carbon in biomass, wetlands, oceans and soil. Many of these solutions also have co-benefits in agriculture, the preservation of ecosystems and biodiversity, and adaptation to climate change. However, most of them have a very large land footprint, which could put them in competition with agriculture and biodiversity. Moreover, concerning forestation, irrigation may be needed in some places, impacting ecosystems, and fire suppression systems may have to be installed to reduce wildfire risk. Perhaps genetically modified plants would be preferred in some climates and certainly to help increase the build-up of carbon in soils, but with uncertainty about indirect impacts in neighbouring environments. Moreover, nature-based solutions may not be permanent and are susceptible to reversal through catastrophic events like fires and floods, and human-made threats (e.g., deforestation, land-use change).
- **Engineered solutions** rely on new industrial techniques to remove carbon from the atmosphere. Methods such as direct air carbon capture and storage (DACCS) are in development and testing. The carbon captured through these technologies can be used in long-lived products like concrete, or sequestered (i.e., contained and mineralised in underground rock layers, for instance, in depleted oil and gas reservoirs). The risk of reversal is lower than in nature-based approaches but still exists.
- **Hybrid approaches** combine nature-based with engineered solutions, like bioenergy with carbon capture and storage (BECCS). The risk of reversal is broadly similar to engineered solutions.

Recognising the need to remove GHG from the atmosphere, a diversity of initiatives have gained traction recently, such as Microsoft’s engagement in reforestation, soil regeneration and DACCS (Joppa et al., 2021), or Swiss Re’s engagement in DACCS. As Microsoft notes, “nature-based methods for storing carbon dioxide are relatively cheap and currently available. But carbon stored in terrestrial ecosystems is at risk of release by fires and pests, for example. Geological storage could be permanent, but today’s technologies are pricey and immature” (Joppa et al., 2021).

A range of new ventures have rushed ahead with novel nature-based approaches, such as sinking seaweed, which could sequester large quantities of carbon. However, the reliability, scalability and risks are unclear, and large uncertainties persist about how much of the carbon would stay stored long enough to help reduce climate change. Moreover, if the practice does not sequester as much carbon as claimed, it could slow or overstate progress on climate change (Temple, 2021).



Impact ratings are from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, apart from 'Measurement and verification', which are based on the authors' judgement.
*BECCS, bioenergy with carbon capture and storage; †$GtCO_2$, gigatonnes of CO_2.

Figure 8 | Carbon-removal strategies (reprinted from Joppa et al., 2021)

Assessment of techniques

The long-term environmental sustainability of the various approaches must be assessed on several criteria, which can broadly be grouped into two categories:

- The permanence of storage (risk of saturation, leakage, reversal);
- The environmental side-effects of their deployment.

Fuss et al. (2018; see their Table 2) have produced a comprehensive review of CDR techniques, including their side effects on the environment and the permanence of storage (saturation and reversibility). This review established the basis of comprehensive assessments of various CDR approaches. See also "Issues of storage: permanence, leakage and saturation" in a Carnegie Climate Governance Initiative 2021 report (Mace et al., 2021) and a simplified visualisation of the impacts of various CDR techniques in Figure 8.

LCAs have been conducted on a wide array of CDR techniques (see Terlouw et al., 2021, for a review). However, a comprehensive understanding of the overall life-cycle environmental impacts of CDR techniques is still missing.

Outcome of workshop discussions

How would you describe the approach taken in the field to discuss (or not) the question of emerging technologies' environmental sustainability, and in particular the approach to:

- **Think (or not) in terms of the need to ensure that the outcome of an emerging technology (or its applications) does not cause damage to long-term environmental sustainability**
  The perceived focus is on enabling CDR as a necessary and required tool to combat climate change rather than on the downside risks. Risks are known to exist but are not adequately understood and addressed.

- **Work to identify possible threats (foresight), conduct early-stage technology assessments and exploratory LCAs**
  Examples can be found of using LCAs to assess CDR technologies (e.g., Terlouw et al., 2021), but the results are difficult to evaluate and compare due to the assessments' incompleteness and a lack of standardisation. This is especially the case for nature-based solutions. Because of greater complexity and uncertainty in natural systems, there are more unknowns related to the carbon

cycle and the risk of leakage. Thus, more rigour is needed in the application of LCAs.

- **Develop suitable technical instruments and governance mechanisms to enable, for example, sustainability-by-design**
  Because the concept of CDR encompasses a wide range of approaches and many uncertainties remain, it is recommended to consider a portfolio of CDR approaches until more knowledge about the most effective and least damaging options is collected. The private sector's innovative power must be utilised but regulated. The regulation of emerging technologies is not a one-shot exercise, but an adaptive and recursive endeavour that includes science and societal values. Regulation aligns technological and economical aspirations with societal expectations.
  The insurance industry has not quantified the environmental sustainability risks associated with CDR to enable risk transfers and currently has no appetite for long-term storage liability (examples in deposits of nuclear waste; see, e.g., Repmann et al., 2021).

- **Balance short-term expected benefits and long-term possible costs**
  There is a sense of urgency to deploy CDR, which makes balanced assessments and governance challenging. Engineered and hybrid approaches, like emerging technologies, are expected to be delivered fast and widely, but doing so may lead to increased risks.
  The long-term costs are neglected or underweighted relative to the long-term benefits, but consideration must also be given to the long-term costs of not deploying CDR. There are fewer short-term benefits in CDR than in other technologies (lack of efficient CO_2 markets and stable economics, unclear customers and investors).

- **Differentiate ethical concerns from environmental concerns**
  Moral hazard is prominent and affects all stakeholders alike, including governments, companies and citizens. The availability of CDR technologies could send a false signal and lower the pressure to reduce emissions. It is important to stress that emission reduction needs to come first. To support that distinction, one suggestion is to define separate targets for emission reductions and concentration reductions instead of endorsing a single, combined net emissions target (Jeffery et al., 2020; Muttitt et al., 2021, regarding the role of CDR in companies' climate plans).

- **Educate researchers, technologists and investors (industry and finance)**
  Transdisciplinary research and multi-stakeholder inclusion can foster transparency and balanced assessments. Examples are scarce but exist, such as (in a similar domain) geothermal projects in Germany, which achieved positive outcomes from a multi-stakeholder approach (Ejderyan, 2021), and ocean fertilisation, which is no longer pursued as a reasonable CDR option because of adverse consequences observed in various experiments. One recommendation is to conduct small-scale demonstrator applications first, using trial and error, to learn from the experiments (e.g., Climeworks, n.d.). However, the risks of deploying large-scale applications can be substantially different (both quantitatively and qualitatively) from those resulting from a sandboxed (contained) experiment.

Is there cause to worry today about the indirect environmental concerns possibly associated with emerging technologies for CDR, including sequestration and storage? Which specific risks, applications or prospective products require further study?

The consequences of large-scale CDR are unknown, and global governance is required. Major risks in the implementation of CDR are associated with:

- Unknown feedbacks on ecosystems and biodiversity;
- The permanency of CO_2 storage sites (risk of reversal; e.g., Alcalde et al., 2018).

Another challenge pertains to advancing multiple agendas with conflicting and competing objectives. In the case of CDR, examples include:

- Clean energy used for energy-intensive forms of CDR (as in DACCS) is not available for other purposes;
- Land used for CDR is not available for agriculture and food production (e.g., Harvey, 2021).

Technology-based CDR seems easier to manage and control (in relative terms) than nature-based solutions. However, the latter are easier to sell to the public.

How can decision-makers include the consideration of long-term adverse environmental impacts in their decisions?
The economics of CDR are key to its implementation, and must include transparency with regard to the risks and benefits, and the quantification and pricing. Efficient and liquid CO_2 trading markets appear instrumental in large-scale CDR deployment. Moreover, an international agreement defining responsibility for risks and the sharing of costs and benefits between the stakeholders is needed.

Where are new approaches and instruments most needed to account for long-term impacts, and how can the current instruments be improved?

- Life-cycle assessments: Greater standardisation and transparency of assessments, using agreed-upon target metrics (e.g., SDG, biodiversity), is required.
- Net effectiveness: Measurement of the “real” net reduction in GHG emissions, that includes the production, operation and eventual dismantling of facilities, is needed.
- Systemic risk governance: The governance of systemic risks is advised to address the uncertainty and complexity of the large-scale deployment of CDR.
- Risk perception: The assessment and shaping of the public’s risk perception through communication and dialogue are heavily influenced by sustainability. Risk perception often differs from evidence-based risk assessments, in particular when considering the risks and benefits of emerging technologies. The affect heuristic, whereby people often rely on emotions rather than on information, can lead to biased estimates, with individuals describing technologies as either “good” (with mostly benefits and nearly no risks) or “bad” (vice versa). People are often genuinely interested in sustainability, an opportunity that decision-makers could exploit, suggesting that society can influence decisions about the need for CDR techniques to fully embrace the sustainability challenge.
- The risk industry: Insurers can help to increase the clarity and transparency of risk assessments, while acknowledging the limitations of data and models.

5.

Space technologies

Background information

The growing space infrastructure is both an asset to improve sustainability on Earth and a cause for concern regarding sustainability in space. Near-Earth space is a highly valuable resource for humanity, used for navigation, communication, Earth observation, technology development, and other purposes. Virtually all societies have become reliant on space-based services in a wide variety of domains. Satellite-based services can enhance the assessment, management and monitoring of environmental risks on Earth, and are thus key enablers of progress towards the SDGs (e.g., Anderson et al., 2017; ESA, 2020; Ferreira et al., 2020; Kavvada et al., 2020; Song & Wu, 2021; UNOOSA, 2020). Concerns are growing, however, that new space activities are being developed without sufficient attention to their adverse effects on the space and terrestrial environments. The manufacturing, launch and operation of spacecraft can have adverse impacts, such as emissions of greenhouse gases, ozone depletion in the stratosphere and the generation of space debris.

The peculiarity of space activities is that they are developed, tested and manufactured on Earth, launched through the atmosphere, and finally provide services to Earth systems. Sustainable space activities must thus encompass impacts on Earth, in the atmosphere and in space. However, while frameworks to assess the impacts of human activities on Earth and the atmosphere have long been developed, frameworks to measure the impacts in space are in their infancy, with work focused on near-Earth space.

Risks associated with emerging space technologies

Innovative space technologies and business models enable new activities, such as the deployment of large satellite constellations, in-orbit servicing, space tourism and asteroid mining. Although these technologies promise a wide range of benefits, they could threaten the long-term use of the space environment and thus have adverse impacts on Earth sustainability. The major concern in this regard is the proliferation of space debris – non-functional human-made objects – which cause a collision risk for operational satellites (Bonnal & McKnight, 2017; Buchs, 2021a). This issue has recently garnered greater attention in academic (Krag, 2021; Nature, 2021) and political (UK Space Agency, 2021) spheres. Addressing the increase of space traffic in an already congested environment requires adequate technologies, policies and practices.

Emerging space technologies are accompanied by several types of risks, which affect both space and terrestrial sustainability (Boley & Byers, 2021; Buchs, 2021b).[12] Risks associated with increased space activities have been neglected and suffer from a lack of research. As a result, policy and business decisions regarding management are either withheld or insufficient. Therefore, risk escalation is possible, with potentially catastrophic consequences on Earth. Examples of risks associated with space activities that can affect terrestrial and space sustainability include:

- Collisions among space objects (see, e.g., Bonnal & McKnight, 2017; Buchs, 2021a);
- Sunlight reflected from space objects and radio interferences from active spacecraft adversely affecting astronomy (Hainaut & Williams, 2020; Kocifaj et al., 2021; Tyson et al., 2020) and stargazing (Venkatesan et al., 2020), with unknown effects on wildlife (Lintott & Lintott, 2020);
- Pollution in the marine environment from rocket launches (Byers & Byers, 2017; Lonsdale & Phillips, 2021) and objects surviving re-entry (Lucia & Iavicoli, 2019);
- Deposition of fine aluminium particulates in the high atmosphere upon satellite demise during re-entry (Werner, 2020);
- Radiative forcing from rocket engine exhaust during launch activities (Pultarova, 2021; M. N. Ross & Sheaffer, 2014; M. Ross & Vedda, 2018).

The extent of the consequence of these risks is largely unknown, and other risks might not yet have

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[12] Not all risks in space affect sustainability. For example, risks to human health in human spaceflight are not related to Earth and space sustainability.

been identified. Some of these emerging risks are not intrinsically new but become salient due to increased space activities. The relatively small-scale space activities of the past did not warrant further study. With the advent of a major space economy, more research into these risks becomes necessary.

Light pollution from the Starlink satellites of the US company SpaceX is an example of the difficulties in addressing potential sustainability issues prior to the deployment of new space technologies. Soon after the launch of the first batch of 60 satellites in May 2019, amateurs and professional astronomers reacted to the brightness of the satellites (McDowell, 2020). While SpaceX has attempted to lower its satellites' impact on astronomy, the results have been mixed (Mallama, 2021).

Assessing and measuring the environmental sustainability of space activities

- **Life-cycle assessment (LCA)**. Several actors in the space industry have identified LCA as a practical tool to monitor and reduce the environmental impact of space activities (see Maury et al., 2020, for a review). The European Space Agency (ESA) has been at the forefront of applying LCAs to space missions and has developed a Framework for Life Cycle Assessment in Space (handbook and database; ESA, 2021). However, space activities are particular as they have impacts on the atmosphere and in space, which require adaptations and the development of dedicated methodologies. Efforts have been undertaken to include the space-debris related impacts within the LCA of space missions (Maury et al., 2017, 2019). The SDGs contain three dimensions of development: economic, social and environmental. Wilson (2019) developed a space-specific life-cycle sustainability assessment framework and database to integrate these three dimensions into concurrent engineering activities to help develop cost-efficient, eco-efficient and socially responsible technologies.
- **Space Sustainability Rating (SSR)**. To incentivise space actors to design missions compatible with sustainable and responsible operations, a consortium led by the World Economic Forum has developed the SSR. The first certifications using this composite indicator of the sustainability of a space mission will be issued to operators in 2022 (Perrin, 2021; Rathnasabapathy et al., 2020).
- **Environmental capacity**. Near-Earth space can be seen as a resource used by active spacecraft and space debris. ESA has developed a metric capturing the consumption of this resource by a space object (i.e., the collision risk induced by an object on orbital neighbours; Lemmens & Letizia, 2020; Letizia et al., 2019). This metric can be used as a tool during the design of a space mission to facilitate the comparison of different mission architectures depending on their potential impact on the space debris environment (Letizia et al., 2020). It can also be integrated into LCAs and will be part of the composite indicator of the SSR.

Outcome of workshop discussions

How would you describe the approach taken in the field to discuss (or not) the question of emerging technologies' environmental sustainability, and in particular the approach to:

- **Think (or not) in terms of the need to ensure that the outcome of an emerging technology (or its applications) does not cause damage to long-term environmental sustainability**
  The space sector lags behind other sectors in its consideration of the environment. Policies have focused on national security concerns and have not taken into account environmental issues. For example, space technologies are exempt from key environmental legislative and regulatory instruments.
  At the international level, space activities are not included in the Montreal Protocol on substances that deplete the ozone layer. The Montreal Protocol does not specifically address emission sources that emit directly into the stratosphere, such as rockets (and aircraft). In Europe, the Waste Electrical and Electronic Equipment directive grants exemptions to space technologies. In the US, the National Environmental Policy Act does not consider space as part of the environment. Moreover, the US entities regulating space activities (Federal Communications Commission, Federal Aviation Administration, National Oceanic and Atmospheric Administration) have a somewhat narrowly defined scope that often does not comprise environmental impact, or at least it is not their focus.
  The impact of space activities on the environment is largely linked to their scale. Increasing space activities will call for more scrutiny towards their impact on the environment and will focus more attention on developing ways to address them.
  The more pressing problem is the sustainability questions that arise from the growth and

expansion of existing uses of space rather than new technologies.
The question of scale is improperly addressed by current regulatory mechanisms, which evaluate satellite or launch licensing applications separately. As a result, only the marginal impact of a handful of satellites or launches is evaluated rather than the complete picture. There is no comprehensive approach to evaluate the long-term environmental impact of space activities. Space activities are not new. Thus, a lot of practices and approaches have been used for a long time and are deeply ingrained, making it difficult to shift and adjust the system towards more sustainable activities. Moreover, space activities are an amalgamation of different technologies.

- **Work to identify possible threats (foresight), conduct early-stage technology assessments and prospective LCAs**
  LCAs have been used to assess the environmental impact of space missions. However, this suffers from not fully robust and tested methodologies and a lack of databases. Impact characterisation is lacking (e.g., no peer-reviewed study quantifies emissions of black carbon or chemical compounds in the high atmosphere from rocket launches). The biggest challenges in conducting LCAs of space missions are at the beginning and end of the value chain (i.e., critical raw materials and post-mission disposal).

- **Develop suitable technical instruments and governance mechanisms to enable, for example, sustainability-by-design**
  Sustainability-by-design has not been directly addressed. However, the most prominent initiative along these lines is conducted by the Clean Space office at ESA and aims to ensure that sustainability is taken into account when designing a mission. The recent initiative to build the Space Sustainability Rating (see previous section) pursues a similar goal.

- **Balance short-term expected benefits and long-term possible costs**
  Space is currently seen as an enabler of other activities on Earth and as providing numerous benefits (connectivity, sustainable development on Earth, etc.). However, there is hardly any balance made with potential environmental impacts. The potential long-term costs are not considered much in assessing new technologies. As the scale and scope of space activities diversify, however, public concerns might request more attention to the balance of risks and benefits. For example, the first space tourism missions launched in 2021 by Virgin Galactic, SpaceX and Blue Origin have increased public attention regarding launches' environmental impact.

- **Differentiate ethical concerns from environmental concerns**
  Ethical concerns have not been directly addressed. Environmental sustainability is only one pillar of sustainability and social and economic aspects should also be considered. The consideration of ethical and societal concerns should at some point be taken into account in a more holistic sustainability assessment (e.g., in LCAs).
  Ethical aspects, such as the appropriation of orbits and resources or the sharing of benefits from space use, form part of space discussions, but seem to be relatively separated from environmental concerns. One area where they intertwine is where new rules or requirements to improve space sustainability may impede emerging space nations' activities or limit the ability of nations to conduct space activities.

- **Educate researchers, technologists and investors (industry and finance)**
  Existing guidelines and best practices are not sufficiently communicated to private actors. Finding a common language between diverse stakeholders is key to addressing issues related to space sustainability.

Is there cause to worry today about the indirect environmental concerns possibly associated with emerging technologies in space? Which specific risks, applications or prospective products require further study?
Although the effects of space-sector activities are minimal at present (according to limited research), they could become much more significant with the increased ease of access to space. Robust scientific evidence on the environmental impacts of space activities is lacking (on the ground, in the atmosphere and in space). For example, more research is needed to assess the impact of launches and re-entries of objects on the atmosphere. Also, it is necessary to consider the full supply chain, from raw materials to end-of-life, when assessing space activities.
The risks associated with forward and back contamination (planetary protection) need to be

regulated before microbial life is brought back in samples from other celestial bodies and then propagates on Earth, or before microbial life is brought to other celestial bodies. It is unclear if the current regulatory regime is apt to address this risk.

How can decision-makers include the consideration of long-term adverse environmental impacts in their decisions?

Good science and sufficient evidence, especially robust studies of different management options, are lacking to help policymakers in their decision-making. In addition, the processes and authorities to evaluate long-term sustainability risks are insufficient. Although the political will is currently missing, preparing for the future is needed now. Greater stakeholder buy-in is also needed. The tools to assess space missions are scarce but space actors seem unwilling to use them to any extent. The disclosure of LCA results or carbon footprints is not common as no actor wants to be perceived as causing negative effects.

Where are new approaches and instruments most needed to better account for long-term impacts, and what kind of instruments are required?

A major issue that impedes the assessment of potential risks to long-term environmental sustainability is the limited access to data. Most of the required information is confidential, and there is no benchmark to assess new technologies or applications.

Governments, which are still the main funders of space programmes, could request that the data necessary for more in-depth environmental risk assessments be made available (e.g., as part of contract requirements). Innovative ways to ensure confidentiality while accessing information necessary to evaluate technologies or their applications need to be developed. However, even with increased numbers of commercial actors, the space domain will remain strategic for militaries around the globe. It is therefore unlikely that data on space activities will become increasingly available in the future. In the US, many space activities are ITAR (International Traffic in Arms Regulations) restricted, meaning that data about them cannot be shared. Moreover, only US citizens can work on certain projects or aspects. Yet a lack of diversity in the workforce impedes the development of a more environmentally conscious mindset and the cultural shift needed.

The following ideas are offered for consideration:

- No entity is responsible for driving the assessment and management of space activities' long-term impacts, and the steps to build such an entity are unclear. It might be useful to create a new industry-wide platform for sharing and promoting R&D on emerging space technologies and their environmental footprint.
- A method developed by the European Commission to measure the environmental performance of any service or good throughout its life cycle, the Product Environmental Footprint is an interesting approach. It would establish category rules describing how to calculate the environmental footprint of space missions, create transparency in the reporting process, and promote third-party verification.
- It is necessary to establish a commonly agreed-upon environmental sustainability threshold (e.g., orbital capacity).

Appendix 2

Workshop programme

Introduction

- What does “environmental sustainability of emerging technology” mean and imply, in contrast to “technology for sustainability”?
- How can environmental sustainability benefit technology developers, industry and investors? Can it be adopted as a selection criterion for financing by research funding institutions?
- Would a risk-based approach be relevant to assess and manage emerging sustainability risks related to technology? Is it possible to translate sustainability issues into a risk-based metric?
- Is there an analogy with the agenda for responsible research and innovation (RRI)?

Session 1

Discussion with Sheila Jasanoff

on the changing nature of technologies and the institutional challenges of governing them.

Session 2

Parallel sessions

Group 1 - Chemicals:
Advanced materials and smart nanomaterials
Group 2 - Synthetic biology:
Gene editing and gene drives
Group 3 - Digital technologies:
Machine learning, AI, cloud computing and blockchain
Group 4 - Carbon dioxide removal:
Removal and sequestration
Group 5 - Space technologies:
Sustainability of earth–space relationships

- Is there cause to worry today about the indirect environmental concerns possibly associated with emerging technologies?
- How can decision-makers include the consideration of long-term adverse environmental impacts in their decisions?
- Where are new approaches and instruments most needed to account for long-term impacts?

Session 3

Learning from across technology domains

- Trends, factors, criteria, instruments: Commonalities and differences across domains.
- Focus on early-stage technology assessments, anticipatory life-cycle analyses and sustainability-by-design.
- What does sustainability mean in each domain (definitions and instruments to assess and evaluate it)?
- What are the common themes (time gaps, emerging technology, emerging markets, ...)?
- What are the instruments for early-stage technology assessment, prospective/ex-ante life-cycle assessment, sustainability-by-design?
- What other instruments might be needed to identify, evaluate, measure, manage and communicate sustainability?

Session 4

Conclusion

- Selection of emerging technologies for further research work organised by IRGC.
- Key sustainability indicators or factors of environmental sustainability to be considered when developing, deploying and regulating new technology.
- Preliminary considerations for developing a sustainability compass to indicate the direction to sustainability.

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Chapters 1 to 5

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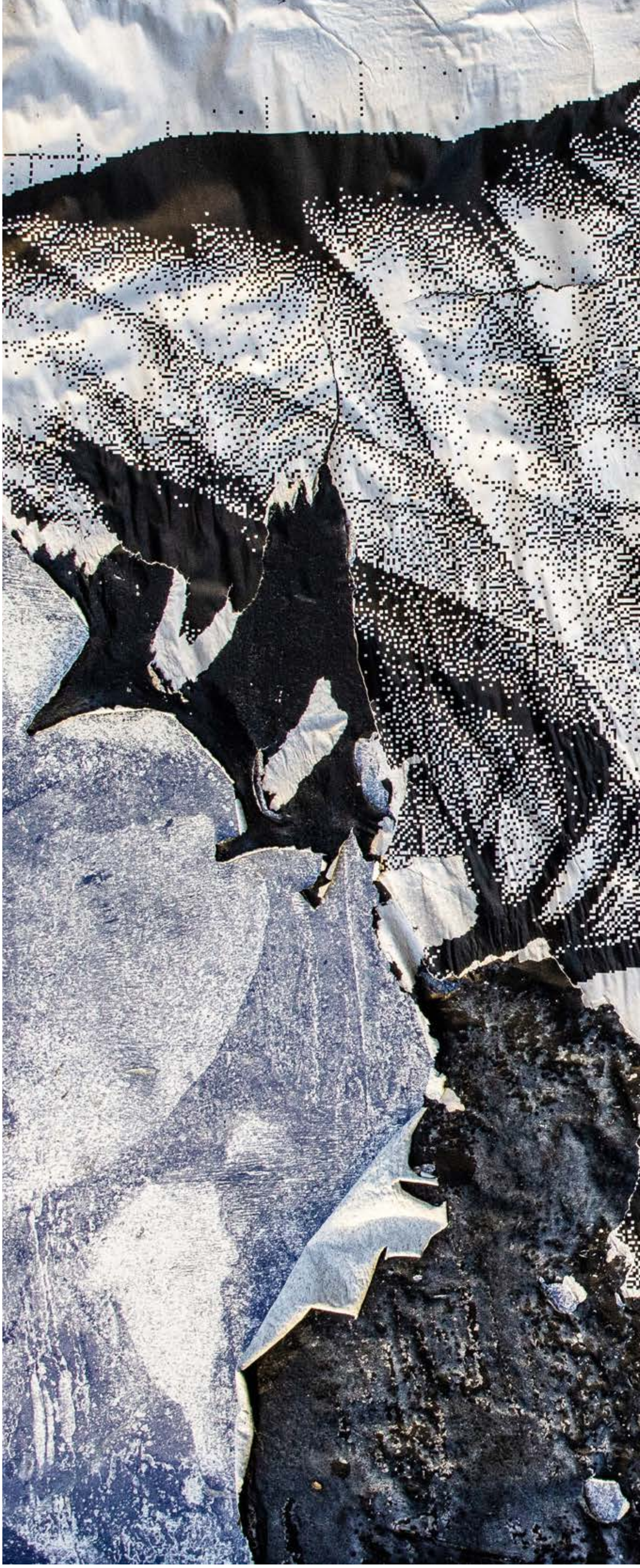

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