This paper is part of the IRGC project "Ensuring the environmental sustainability of emerging technologies".

Suggested citation: Sachs, R. (2022). Ensuring environmental sustainability of emerging technologies — the case for applying the IRGC emerging and systemic risk governance guidelines. In M.-V. Florin (Ed.) (2023). *Ensuring the environmental sustainability of emerging technologies* (Edited volume). Lausanne: EPFL International Risk Governance Center. DOI: 10.5075/epfl-irgc-298445

Ensuring environmental sustainability of emerging technologies – the case for applying the IRGC emerging and systemic risk governance guidelines

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Table of contents

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Introduction

Risks from emerging technologies can have new characteristics. When they are radically new, there is a general lack of data and risk assessment methods. Risks may even be systemic, i.e., they arise from the complexity of the technology itself and/or their interaction with the environment.

In this paper, we propose a set of risk governance strategies selected from the EPFL International Risk Governance Center (IRGC) "Guidelines for the governance of emerging risks" (IRGC, 2015) and "Guidelines for the governance of systemic risks" (IRGC, 2018). The selection is based on insights from the IRGC project "Ensuring the environmental sustainability of emerging technologies" (ESET) (IRGC, 2022) and an analysis of past examples[2]. The paper aims to provide a bridge for the transfer of generic concepts and principles into practical recommendations for ensuring the environmental sustainability of emerging technology outcomes. We start by summarising the defining properties of emerging and systemic risks, motivating the relevance of the two corresponding guidelines in the ESET context (section 1) and reviewing certain governance strategies for ESET (section 2). We use several examples of how some risks involving novel technologies or products were handled in the past, e.g., the use of chlorofluorocarbons (CFCs), and emerging technologies, such as for carbon dioxide removal (CDR) and sequestration, gene drives, and operations in outer space, to illustrate the application of the selected strategies in the case of each technology and their operationalisation.

1. Background and context

Emerging technologies are developed for a purpose, including but not limited to improving sustainability. Ensuring the environmental sustainability of emerging technologies is the core objective of the IRGC project ESET. Environmental sustainability is at risk if either the target benefits of the technology are not realised as intended, or negative side-effects (ancillary risks) are not sufficiently mitigated and reduce the target benefit.

Emerging technologies within this project are defined by the following set of criteria (Rotolo et al., 2015): radical novelty, prominent impact, fast growth, ambiguity, and uncertainty. Complexity and transformative power are not strictly part of this definition. However, the combination of defining features of emerging technologies and analysis of past emerging technologies lead to the conclusion that the risk governance of emerging technologies needs to address complexity and transition risks as well. For example, rapid digitalisation has changed and is still changing society's entire way of living and working.

We can reasonably assume that emerging technologies can lead to both emerging and systemic risks. These types of non-classical risks require novel approaches in risk management. IRGC has developed conceptual frameworks for these risks[3]: the "Guidelines for emerging risk governance" (IRGC, 2015) and the "Guidelines for the governance of systemic risks" (IRGC, 2018). In this paper, we are mainly interested in the applicability of these guidelines to specific emerging technology use cases. We do not provide a comprehensive overview of the guidelines here, beyond a brief summary of the basic concepts and necessary terminology.

1.1 Emerging risks

Emerging risks are often associated with new technologies. They are either new risks, or known risks that become apparent in new, unfamiliar, or changing context conditions. The smartphone provides a classic example of existing technology (computers) applied in new contexts (mobile use). The different use patterns changed how we access digital information and revolutionised social interaction, thereby impacting existing economic and societal structures, data privacy and security.

[2] See also the paper written for the ESET project by Rainer Sachs, "Risk governance of emerging technologies: Learning from the past" (2022).
[3] See www.epfl.ch/research/domains/irgc/concepts-and-frameworks/emerging-risks and www.epfl.ch/research/domains/irgc/concepts-and-frameworks/systemic-risks

Emerging risks are characterised by uncertainty regarding their potential consequences and/or probabilities of occurrence, i.e., these properties cannot be quantified. Quite often, emerging risks are unanticipated and manifest as surprises. There is typically a lack of knowledge about causal or functional relationships between the sources of emerging risks and their environment. Emerging risks are not restricted to the domain where the technology is applied but can occur in seemingly unrelated fields.

1.2 Systemic risks

Emerging technologies are applied in a world characterised by an increasing interconnectedness within and between systems. We follow the IRGC definition of the term "system" as being a "regularly interacting or interdependent group of items forming a unified whole" (IRGC, 2018).

Due to the interconnectedness and complexity of systems, conventional risk governance approaches reach their limits. Risk management by fragmentation of risks into individual categories and of the environment into isolated systems has been successful in the past. In the first step of such an approach, individual risks are identified, modelled, and mitigated separately. Only in the second step their possible connections and dependencies are considered, and individual risk models are aggregated. However, for complex systems, the fragmentation approach is too reductionist and limited in scope. The key to identifying and managing risks in complex systems is understanding and modelling the dependency structure first. The vital information is in this structure, not in the individual system nodes. Defining properties of complex systems like emergence and adaptation arise from the interaction of system nodes.

Systemic risks typically evolve in interconnected systems. They are characterised by contagion and proliferation processes (ripple effects), frequently on the basis of a network structure. A seemingly harmless event, e.g., individual failure, disruption or accident, poses a threat to the entire system and can even cause a complete collapse (Lucas et al., 2018). Systemic risks are stochastic and often appear seemingly out of the blue.

The application of current and future emerging technologies can be expected to cause systemic risks. Emerging technologies can diffuse across system borders, and so will the associated risks. Isolated islands will be scarce in interconnected system landscapes, and the conventional containment approach of risk management will not be effective anymore.

2.

Risk governance for ESET

In this section, we provide a selection of elements from the emerging risk and systemic risk governance guidelines (IRGC, 2015, 2018) to the risk governance objectives of ESET. The selection is based on examples from the technology domains of the ESET workshop (IRGC, 2022) and the lessons learned from past examples.

This paper thus suggests elements for consideration towards the sustainability governance of emerging technologies by reflecting specifically their non-conventional emerging and systemic risks to the environment. The objective of this paper is to recommend risk governance strategies and offer ideas for their operationalisation for specific applications with a focus on environmental sustainability. We illustrate these strategies with examples from specific technological applications and products.

There is no one-size-fits-all solution for the environmental risk governance of emerging technologies, which each has its specific challenges, such as uncertainty and the need to prepare for surprises or complexity. Moreover, there may or may not be a responsible organisation (risk owner) for the risk aspects of that specific emerging technology. Hence, ensuring the environmental sustainability for a particular emerging technology will require several elements, different for each emerging technology. The whole set of elements provides a preliminary collection of risk governance strategies for consideration, and the applicability of each element can be checked.

2.1 Implement strategies to resolve uncertainty

Emerging technologies are characterised by significant uncertainty. Uncertainty denotes a cognitive state of incomplete knowledge resulting from a lack of information and/or disagreement about what is known or even knowable. In conventional risk framing, for instance, an event is regarded as uncertain when the probabilities or outcomes are not precisely known. The lack of knowledge can, however, also pertain to the type of consequences, the severity of the consequences, or the time or location where and when these consequences may occur (IRGC, 2017).

In the context of environmental sustainability, only a limited subset of unexpected consequences of emerging technologies can be assessed quantitatively. Most consequences can be assessed only with qualitative methods, if at all. It is often challenging to imagine what has never happened before; the context (environment) is often difficult to describe and frame. Scientific unknowns, whether tractable or intractable, contribute to risks being unanticipated, unnoticed, and over- or underestimated.

In order to resolve uncertainty in a systematic manner, it is useful to distinguish between different types of uncertainty. Kunreuther et al. (2014) provide a classification of the term in the context of environmental and climate risks, which is briefly summarised here:

- **Paradigmatic uncertainty** results from the absence of prior agreement on the framing of problems, the methods for scientifically investigating them, and the difficulty of how to combine knowledge from disparate research traditions.
- **Epistemic uncertainty** results from a lack of information or knowledge for characterising phenomena.
- **Ambiguity** implies that there are vague, but usually differing beliefs about the likelihood of events occurring. If people are not able to form any beliefs about probabilities, this particular case is termed complete ignorance.
- **Translational uncertainty** results from scientific findings that are incomplete or conflicting, so that they can be invoked to support divergent policy positions.

The following strategies for emerging risk governance are particularly useful for addressing and resolving different types of uncertainty related to emerging technologies:

- In the case of epistemic uncertainty about an emerging technology outcome, more **research and monitoring** are necessary. Knowledge gaps must be identified and can possibly be filled through fundamental research and the transfer/application of existing related knowledge.
- What remains unknown or even, in principle, unknowable, must be clearly articulated and explicitly made transparent. Knowing the **limits in understanding and modelling** is the prerequisite for improving risk governance of emerging technologies.
- When little is and can be known about a technology that potentially has severe negative consequences, “wait-and-see” strategies must be avoided. Instead, **precaution-based and resilience-focused strategies** should be considered. They are particularly relevant where the ratio of knowledge to ignorance is low, as with emerging technologies. They can ensure the reversibility of critical decisions (e.g., about the deployment of emerging technology in the environment) and increase the environment’s coping capacity so it can withstand shocks or adapt to new conditions.

Particular attention to address cognitive biases is needed. There is a tendency to underestimate surprises systematically, assume that lessons have been learned from the past, or overestimate the ability to make judgments under unpredictable circumstances. Problems of collective judgment, such as group biases towards cautious or risky shifts, are frequent in situations of ambiguity. Organisations may show inertia and reluctance to change because of vested economic or political interests.

> **Exemplification**: The failure of risk governance of neonicotinoids and CFCs in the past can clearly be attributed to two reasons: First, the ubiquitous lack of knowledge and understanding pertains not only to the (arguably unintended) adverse consequences of emerging technologies, but also to the methods required for risk assessment (epistemic and paradigmatic uncertainty). The second reason is that vested interests may lead to wilful ignorance of early warning signals or research outcomes. Another example is the failure to act upon the outcomes of scientific research on the consequences of greenhouse gas (GHG) emissions.

Therefore, it appears wise to ask the following questions, even before beginning the risk assessment of radically new technologies, and find meaningful answers to them:

- How suitable are the existing risk assessment methods, and how should they be modified or re-

developed from scratch? For example, Cucurachi & Blanco[4] show this for life cycle assessment (LCA), when both the technology and the context of its application change from the current situation.
- How can the concept of "environmental sustainability" be meaningfully operationalised? What exactly does "environment" mean, and which parts are included or intentionally excluded in the assessment?
- How do we define, articulate, and set the risk appetite, i.e., the tolerances of stakeholders towards potential harm to the environment?
- How can we improve responsible decision-making, e.g., by the design of structures and processes to reduce the impact of cognitive and organisational biases?
- What is needed to avoid wilful blindness and the tendency to interpret harmful consequences as unforeseeable surprises? Unfortunately, it appears more acceptable to the public if decision-makers are caught by surprise (or pretend to be) than if they knew in advance and their decisions turned out to be wrong, for whatever reason.

The concept of post normal science (PNS) approach (Funtowicz & Ravetz, 1994) explicitly includes a greater spectrum of **values and beliefs** in risk assessments. PNS involves the consultation of extended peer and stakeholder communities (beyond scientific researchers) to understand and interpret the limits of knowledge and their influence on policy decision-making. Such discourse-based approaches are also recommended by IRGC (2017) for risk situations characterised by ambiguity, where stakeholders have different beliefs about the benefits and risks of a particular technology. Such strategies aim to create tolerance and mutual understanding of conflicting views and eventually find ways to resolve the conflicts.

> Exemplification: Gene drives technology is an emerging technology that can lead to significant and permanent changes in entire populations' genetic information, with possible long-term and far-reaching impacts on the whole ecosystem.[5] Adopting a PNS approach is suggested when uncertainty is considerable, and impacts on the environment can be drastic.

2.2 Overcoming obstacles to the systematic consideration of early warning signals

Concerns about long-term environmental sustainability require attention to early warning signals and preparation for unexpected events. Hence, proactive governance of emerging technology aims to enhance anticipation and forward-looking capabilities.

Early warning aims to make sense of weak signals indicating whether the deployment of an emerging technology might positively or adversely impact the environment. Making sense of weak signals is much easier if they are actively sought, and if the search strategy is based on scenarios, which must already be part of the technology development process.

Risk mitigation options are available throughout the process (Figure 1). Early in the process, options may be more abundant and broader, especially as precautionary and preventative approaches may be considered. However, early mitigation may conflict with innovation, which it may stifle. Late mitigations come at higher costs in case environmental damage has already occurred but may be more targeted

> Exemplification: The detection of the ozone hole was the result of long-term systematic monitoring (Farman, 2001). CFCs were not expected to deplete the ozone layer in the remote stratosphere to such an extent, even if their potential to break down ozone molecules had already been known for over a decade.

Explorative scenarios aim to find answers to "what if?" questions and acknowledge the possibility that context conditions could differ from today. Divergent futures may result from known or unknown trends and events for which a probability distribution does not exist. Explorative scenarios look into alternative views of the future and create plausible stories from them. For example, one could ask how the environment — even in the distant future and distant geographically from the intended application of the emerging technology — will develop and could be adversely impacted.

[4] See also the paper written for the ESET project by Stefano Cucurachi and Carlos F. Blanco, "Practical solutions for ex-ante LCA illustrated by emerging PV technologies" (2022).
[5] See also the paper written for the ESET project by Jennifer Kuzma "Gene drives: Environmental impacts, sustainability, and governance" (2022).

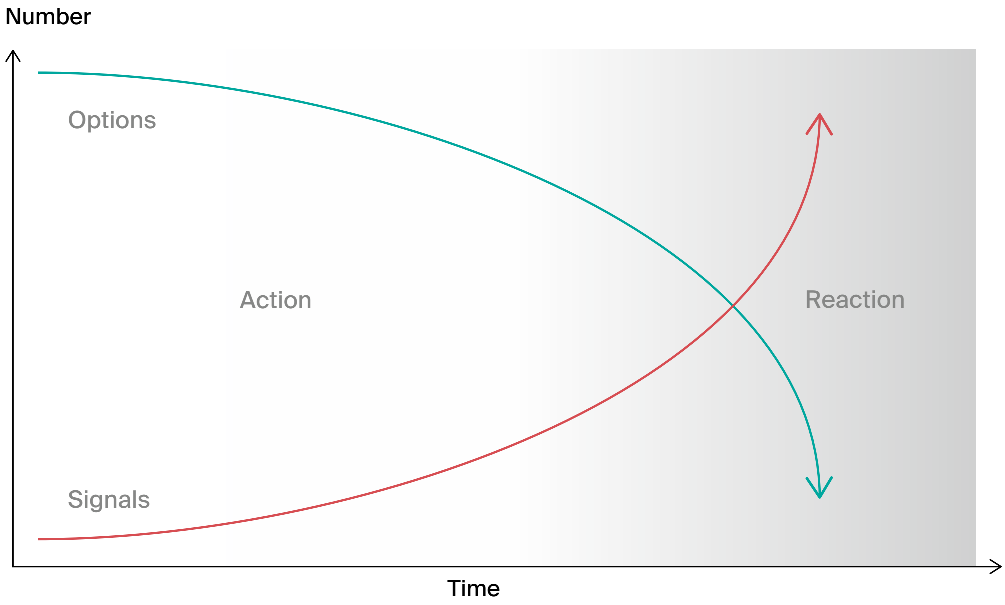

Figure 1 | Indication of damage (signals) increases over time, but risk mitigation options decrease in parallel. Eventually, the decision space changes from "action" to "reaction"

In other words, these scenarios contain possible development paths for both the emerging technology and the environment, whether or not those changes would be attributable to the technology. In particular, the environment needs to be observed for potential precursors of major changes and transitions that might affect the applications of emerging technologies.

Vulnerabilities and potential impacts of emerging technology on the ecosystem need to be identified and included in scenarios and early warnings.

Exemplification: Carbon dioxide removal (CDR) includes a set of technologies necessary to meet emissions targets in our attempts to combat climate change. In broad terms, CDR proposals can be grouped into engineering-based methods (e.g., direct air carbon capture and storage) or nature-based solutions (e.g., forestation).

While nature-based solutions appear easier to sell to the public, these approaches are typically more complex and their environmental carbon cycles are less understood. Societal preferences may be due to biased perceptions of risks and benefits, especially in environmental matters where "nature" is trusted more than "technology." In other words, there may be some doubts regarding the ability of technology to fix problems that were caused by technology in the first place.

To avoid mistakes made with the early development of large-scale liquid biofuel production case in the 2010s, CDR **scenarios** should pay special attention to the following aspects regarding nature-based solutions:

- What are the economic, social, and political impacts of changing land use? How are the conflicts with agriculture for food production resolved (Harvey, 2021)?
- What is the anticipated change of the environment due to climate change, independent from but also directly and indirectly impacted by large-scale deployment of CDR (feedback loops)?
- Biodiversity and local ecosystems will most likely be adversely affected (increasing monoculture). How is this risk-risk trade-off managed?
- How can we assure there is a net reduction of CO_2 by converting arable land or carbon sinks (e.g., wetland, peatland) for, say, forestation, possibly requiring artificial irrigation and energy (what would be their source?) that could subsequently not be used for other purposes?
- How to ensure that CDR does not aggravate climate change? The permanency of CO_2 storage needs to be ensured, and sequestration must not be reversible (Alcalde et al., 2018).

Scenarios can help decision-makers **structure and organise the many uncertainties** arising from an emerging technology, as well as from the complex character of their political, social, and natural environment. However, they are not meant or constructed to predict the future. Even with the most sophisticated analysis of future developments, unexpected events will occur.

2.3 Strategies to prepare for unexpected events

Preparation is required for sudden events with adverse consequences (crises, disruptions, accidents), which may also prevent the effective deployment of technology and mitigation strategies. Therefore, the risk governance process must contain specific measures to **build resilience** to prepare for uncertain and unknown shocks and stresses.

Unanticipated barriers (occurring in the technology and/or the environment) that may come up during the process must be addressed, sometimes requiring drastic **revision of decisions and swift adaptation**. Governing risks in a systems approach requires engaging in deliberative exercises to identify and overcome barriers and obstacles before they grow (Figure 1 above).

Exemplification: CFCs were utilised for many decades without concern about adverse impacts on the environment. This is because the compounds of CFCs are chemically inert in the lower atmosphere and essentially nontoxic. However, there is a risk-risk trade-off in this specific safety design that was largely ignored at the time: because of their inertia, CFCs have extremely long persistence times (40–150 years) and can reach remote areas far away from their original deployment region. While CFCs do not react easily with other chemicals in the lower atmosphere, they become highly reactive as they move into the stratosphere where UV radiation can break up CFC molecules.

Scientific evidence of environmental harm had been available for more than a decade before action was taken. Only a sense of urgency created by media exposure and public attention to the ozone hole, and the availability of alternative substances (substitutes) led to a relatively fast decision to phase out CFCs.

Exemplification: The adaptation of the EU biofuels regulations in several waves between 2003 and 2018 illustrates a policy response to a better understanding of the environmental and societal impacts caused by the growth of biofuel crops, which were threatening one of the initial targets of improving the economic situation of local farmers (cf. also next section).

2.4 Understand and embrace complexity

Complexity could lead emerging technologies to adversely impact the long-term sustainability of the environment or the climate. Low predictability, limited modelling capabilities and emergence are prominent features of connected complex systems. Emergence means that the overall behaviour of a system, composed of interacting elements, can be qualitatively different from the simple aggregation or extrapolation of the behaviour of individual elements.

Complex adaptive systems can also exhibit feedback mechanisms that amplify change or perturbation that affects them. Positive feedback tends to be destabilising and can thus amplify the likelihood or consequences of risks from emerging technologies. For example, burning fossil fuels impacts the Earth's climate system and triggers positive feedback: GHG emissions causing the melting of permafrost, leading to more GHG emissions, or reduced ice cover on glaciers and the arctic reducing the surface albedo leading to more energy from the sun being absorbed on Earth.

It is important to realise that feedback is not necessarily a process within a single system node, e.g., the natural environment, but it can involve multiple nodes across different system boundaries: from technology to society to politics to environment. This makes identification and assessment a challenging task that can only be accomplished by strict adherence to the system approach combined with active transdisciplinary collaboration and, for example, adaptive regulation.

Exemplification: The increased growth of biofuel crops not only triggered the obvious food vs fuel debate (direct consequence), but also caused unexpected harm in the societal domain (changing land ownership and local structures as indirect consequences). The target benefit remains questionable: previously unused land (forests, peat) serving as a GHG sink is converted into agricultural land, thus threatening the emissions reduction targets (Hunsberger, 2015).

This is typical for a systemic risk situation, where risk mitigations may backfire: the attempt to address the risks of climate change by increasing biofuel production at a scale that would disrupt ecosystems caused harm in other connected systems. Adapting regulations in the EU in several waves from 2003 to 2018 has been a largely successful response to complexity.

Systemic risk governance strategies aim to improve the system's capacity to absorb and recover from shocks and stresses and adapt to new context conditions. Rather than avoiding complexity and working against it, one should use the inherent tendency of complex systems to self-organise and thereby create a stable, ordered state or controllable transition. For example, the design of the emerging technology could contain features of negative feedback to diminish the potential for adverse environmental impact. The concept of Safe and Sustainable by Design (SSbD) aims explicitly at developing and implementing such aspects right from the initial development process. We refer to a recent report from the Joint Research Centre (2022) for a comprehensive review of SSbD.

Exemplification: Smart materials (SMs) are adaptive substances that can change certain critical properties during use.[6] Because of their changing properties, SMs pose crucial challenges from a risk perspective: one cannot predict with sufficient certainty the behaviour of the materials and their possible adverse effects after release into the environment. SMs could therefore be designed with very specific and limited adaptive features or finite lifetimes.

Risk governance should adopt a system approach whereby the environment in which SMs are intended to be deployed is scrutinised:

- What are the possibilities to strengthen the environment's robustness and resilience by introducing coping mechanisms if the SM behaviour is outside its intended regime?
- Reverse stress tests could be conducted: starting from the assumption that an essential part of a system would collapse or that critical ecosystem services would be disrupted, what could be the possible causes (individual or combined), and what role could SMs play in such an event?
- Which design of SMs can help to avoid system damage?

Exemplification: Similar considerations are recommended for deploying **gene drives technologies**[7] where, in contrast to natural (Mendelian) inheritance where only 50% of the genes are passed to the offspring, the modified genetic information is passed dominantly to future generations – possibly up to 100%. In theory, releasing just a few modified organisms could permanently change entire populations. As a safety measure, gene drive systems can also be designed to be limited in geography or spread, or to be reversible. As of today, laboratory experiments have been conducted, but no gene drives have been released into the environment.

As has also been observed in the case of liquid biofuels[8] the solution to narrowly defined problems will typically cause the problem to move to adjacent systems. This is very relevant for the planned applications of gene drives, e.g., the eradication of invasive species or disease vectors, and illustrates again the risk-risk trade-off that often occurs in risk governance (Wiener, 1998): the mitigation of a particular risk can create countervailing risks with possibly even greater harm. In the case of gene drives, this translates to the fact that removing a species (whether native or invasive) "could produce unintended cascades that may represent a greater net threat than that of the target species" (Webber et al., 2015).

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[6] See also the paper written for the ESET project by Steffen F. Hansen, Freja Paulsen and Xenia Trier, "Smart materials and safe and sustainable-by-design – a feasibility and policy analysis" (2022).
[7] See also the paper written for the ESET project by Jennifer Kuzma, "Gene drives: Environmental impacts, sustainability, and governance" (2022).
[8] See also the paper written for the ESET project by Rainer Sachs, "Risk governance of emerging technologies: Learning from the past" (2022).

2.5 Implement ways to assign accountability despite a lack of risk ownership

Effective risk governance needs adequate structures and resources. Learning from past examples shows that there is a general lack of resources for the assessment and management of risks from new technologies. This may be caused by an unbalanced prioritisation of the preferred scenario where target benefits would be achieved without collateral damage. Resources and competencies required for the identification, prioritisation and development of alternative scenarios are often profoundly underestimated. Few organisations are willing to invest sufficiently in this expensive and time-consuming task and in forward-looking risk assessment processes, methods and competencies.

> **Exemplification:** The case of **neonicotinoids** provides the perfect example for the consequences of low priorities on understanding the risks: the focus was (and still is) on the benefits of pesticide use. There were insufficient resources and funding in the development phase for a scientifically sound and fair risk governance process (Maxim & van der Sluijs, 2013). There were no functional organisational structures in place to manage the risk governance process and assign responsibilities to the stakeholders. Ultimately, after a long and highly political debate, major stakeholders with conflicting interests could not arrive at a mutually agreeable solution.

IRGC (2015, 2018) emphasises the need for a risk governance facilitator and defines the roles of a "navigator" for systemic risks and a "conductor" for emerging risks. The facilitator's role combines elements from both "navigator" and "conductor", coordinates and leads the internal and external stakeholders involved in the assessment, management and communication of risk issues. The question of ownership and oversight is crucial in structures of distributed responsibility if risks are or may be systemic: everyone is responsible for some part of the system, but no one has the responsibility to act on the entire system.

The facilitator does not need to be the "subject matter expert" for the specific technology. They should be competent in risk governance topics, however. Their responsibility is to facilitate the risk management process. For example, the European Food Safety Authority (EFSA) partially functions as a facilitator in questions related to food security in the EU. The Office of Technology Assessment at the German Bundestag (TAB) has a similar role in Germany.

The core tasks of the facilitator are the following:

- Managing and enabling interaction among stakeholders for collaboration, networking, learning and experimentation;
- Bringing new knowledge to the process and familiarising stakeholders with multi-disciplinary work;
- Organising capacity- and competence-building of stakeholders (e.g., behaviours, attitudes, culture);
- Working to break silos of whatever form (disciplines, sectors, stakeholder groups);
- Validating and legitimising the technical methods and approaches used and developed during the process;
- Ensuring that scientific concepts are translated into understandable concepts for effective risk management and policy; and
- Reporting, reviewing, and monitoring results and performances to demonstrate their relevance.

Emerging technologies, as they are defined in the context of this paper, are potentially pervasive and can diffuse across system boundaries with possibly global reach. Some emerging technologies are designed explicitly for global application, e.g., CDR or space technologies. Such a global technology requires global risk governance and regulation, and the responsibility needs to either sit within an internationally legitimised organisation or be orchestrated within a cooperative network of stakeholders. In any case, there needs to be a dedicated facilitator for the risk governance process.

> **Exemplification**: The paper on space technology[9] demonstrates that risk regulation for access to and use of outer space is still in its infancy. International treaties were adopted before space activities had any significant impact on the

[9] See also the paper written for the ESET project by Romain Buchs, "Ensuring the environmental sustainability of emerging space technologies" (2022).

space environment and before environmental sustainability became a concern. This may partly be attributable to the political and military interests in space technology. The increase in private space activities will change the picture. In general, risk governance and regulation appear to trail behind technological development.

If regulation is insufficient to manage ET's environmental risks, **liability regimes** (i.e., attributing responsibility in case of harm and compensating damage) could be used as additional policy instruments.[10] Liability regimes complement regulation and can address gaps in regulation, but there are limitations. The typical challenges of protecting the commons, e.g., unowned land or space, via liability instruments are (1) the lack of claimants and (2) undefined or undefinable compensable harm. If a private firm causes harm to the environment, there may be no one to make a claim, or there may be no one who has suffered compensable harm or can quantify the harm. With no cost for externalities, there is no direct incentive for private actors to not only avoid damage to the commons, but also to contribute positively to environmental sustainability.

As one partial solution, regimes of public interest litigation have been established in the EU. They create incentives for public and private organisations to initiate lawsuits against companies that have harmed public goods, thus indirectly increasing the company's interest in avoiding harm.

Risk governance for protecting the commons should, therefore, not just focus on identifying, assessing, and mitigating adverse outcomes from emerging technologies, but also on the issues of responsibility and the design of incentives to avoid harm to the environment. As pointed out by Albrecht & Parker (2019), one of the critical success features of the Montreal Protocol was the promotion of compliance and management of non-compliance.

2.6 Strive for clear communication and broad framing of risks and opportunities

The framing of a potential threat from an emerging technology as a risk to the environment may have significant strategic consequences. The target benefits of the technology are usually the primary focus. Social dynamics (political, societal, media interest), counter incentives, and inappropriate or insufficient incentives may deter stakeholders (decision-makers, technology experts and scientists) from recognising, reporting, and addressing new risks or even framing certain issues as risks. However, a too strong focus on the risks of the technology, although they undoubtedly exist, could be misinterpreted as an undue obstacle to achieving the benefits expected from the emerging technology.

Collins et al. (2021) highlighted this tension in the context of the transition to a low-carbon society and economy. Ignoring or not paying sufficient attention to the risks upfront could cause the failure of the technological deployment. Risks that may materialise later in the process could turn out to be insurmountable. Identifying and assessing obstacles and barriers is ultimately required for successful applications.

Exemplification: The Montreal Protocol to ban CFCs is a landmark example of a collaborative multi-stakeholder decision and regulation of environmental risks. By carefully attributing responsibilities and providing opportunities for innovation, the process contributed to the success of the Protocol.

Trust, mutual understanding and appreciation are key ingredients for an efficient and effective risk culture and must be fostered. Successful risk governance requests that stakeholders can communicate and collaborate on seemingly conflicting perspectives: minimising risks and achieving benefits simultaneously. This has always been challenging and could become even more so. Currently, there appears to be a tendency towards a zero-risk appetite in the public discourse and a concentration on precaution and avoiding all risks. But if technological innovation is possible and appears economically feasible, there will be someone doing it and ignoring the risks.

[10] See also the paper written for the ESET project by Lucas Bergkamp, "Liability's role in managing potential risks of environmental impacts of emerging technologies" (2022).

For some emerging technologies, the concept of essentiality might offer a way to define risk appetite and possibly agree on a mutually acceptable level. For example, in the case of CDR, there appears to be a global consensus that the technology is urgently needed to combat climate change. However, there is insufficient scientific and public understanding of risks and benefits, and societies seem unwilling to bear at least some of the risks.

Risks from emerging technologies are likely to require a broader framing of the issue. This is due to their potential systemic properties. The key is a willingness to explore and communicate one's exposure and vulnerability to risks across system boundaries and different time horizons. Opportunities to take action eventually need to be identified.

The perceived or actual need to develop and implement emerging technologies is an important obstacle to broader framing and comprehensive risk governance. This is because short-term benefits are typically prioritised over the burden of possible long-term costs. Like in many other domains, short- and long-term negative externalities are not internalised in calculating actual costs.

However, it is not a matter of different time horizons only. The case of CDR illustrates the tension between risk and benefit, which are both long-term. The urgency to address climate change requires deploying CDR on a large scale and as soon as possible. But at the same time, there are identified and potential adverse side effects (countervailing risks), and target benefits remain uncertain. It is important to realise and openly address the influence of urgency on the perception of long-term risks and benefits. Urgency must not lead to wilful blindness or conscious neglect of possible systemic properties and hamper the appropriate framing and analysis.

3. Recommendations and conclusions

The specific properties of emerging technologies, i.e., radical novelty, uncertainty, ambiguity, fast growth and prominent impact, make a plausible case for applying the IRGC guidelines for emerging and systemic risks governance. In this paper, we analysed how the generic concepts from the guidelines can be applied to ensure the environmental sustainability of emerging technologies.

Table 1 | Recommended risk governance strategies and their possible operationalisation for ensuring the environmental sustainability of emerging technologies

Understanding and embracing complexity	• Accept low predictability, limited modelling capabilities and emergence • Beware of feedback mechanisms that can lead to amplification • Expect risk mitigations to backfire • Support and strengthen the ability of the system to self-organise and self-control • Improve the system's capacity to absorb and recover from shocks and stresses
Implementing strategies to resolve uncertainty	• Enable and conduct more risk-related research and monitoring • Identify and know the limits in understanding and modelling • Consider precaution-based and resilience-focused strategies • Address cognitive biases
Overcoming obstacles to the systematic consideration of early warning signals	• Enhance anticipation and forward-looking capabilities • Actively search for early warning signals, vulnerabilities, and potential adverse impact • Develop explorative scenarios for both the technology and the environment (system perspective) • Imagine divergent futures to structure and organise a broad spectrum of possible development paths
Implementing strategies to prepare for unexpected events	• Build resilience to prepare for uncertain and unknown shocks and stresses • Allow for revision of decisions and swift adaptation

Past and current examples of emerging technologies are analysed in the ESET project. We selected specific elements from the IRGC frameworks based on these case studies. We suggest the following strategies and their operationalisation for risk governance, presented in Table 1 below.

In addition, governing risks in complex situations demands careful attention to the execution of strategies: "how" policy decisions are taken is equally important than "what" is decided (Kupers, 2020). The risk governance strategies in Table 1 above belongs predominantly to the "what" class. Table 2 below presents some key conditions of success for implementing strategies: accountability communication and framing relate mainly to the "how".

With these strategies and their operationalisation, we link the guidelines for emerging and systemic risk governance and their application in concrete cases of past and current emerging technologies. While there is no perfect solution and no rigorously defined emerging technology risk governance framework (yet), we believe the examples demonstrate how the proven principles from IRGC guidelines for emerging and systemic risk governance can be utilised in specific cases of emerging technologies.

Table 2 | Selected conditions of success for implementing risk governance strategies

Implementing ways to assign accountability for risk governance despite lack of risk ownership	• Balance the attention between target benefits and potential adverse risks • Estimate the required resources and competences adequately • Implement a dedicated owner for risk governance ("facilitator") • Avoid structures of distributed responsibility in systemic risk situations
Implementing strategies to resolve uncertainty	• Looking for risk may be seen as an obstacle to innovation, but ignoring risks upfront can cause the failure of technology • Risks from emerging technologies are likely to require a broader framing of the issue (system view) • It is important to understand social dynamics and risk perception

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