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Introduction

Marie-Valentine Florin[1]

In 2021, the EPFL International Risk Governance Center (IRGC) started work on a project about the issue of "ensuring the environmental sustainability of emerging technologies" (ESET)[2]. The project reviews concerns about the potential environmental unsustainability of some emerging technology outcomes, i.e., unfolding in the future, and evaluates the extent to which these concerns could be more effectively addressed in technology design and development, before large-scale deployment.

It is no longer sufficient to let people innovate and then address negative externalities with regulations. What is new is that the potential negative impacts of some of today's emerging technologies (e.g., machine learning, climate engineering, advanced chemicals, synthetic biology) could occur at an unprecedented scale and speed, and be irreversible. Some technologies could quickly impact major systems on which we depend (natural ecosystems, climate). Therefore, we cannot use the "trial and then correct the errors" method often used in the 20th century. Nor can we wait until we have extensive datasets. We must become better at anticipating, recognising patterns and intervening proactively, even with limited data available.

In this project, IRGC's goal is thus to improve the ability to detect and address a risk to environmental sustainability early in the technology development process, before usual risk and impact assessment is possible. IRGC's priority is not to explore conditions of success of emerging technologies developed *for* environmental sustainability, but to explore what could be done to ensure that *any* emerging technology does not appear later in its deployment to cause indirect, adverse consequences on the environment. A first report, "Ensuring the environmental sustainability of emerging technologies"[3], was published in March 2022. The report describes the current attitude towards the issue in various technology domains and instruments available or considered to help reach the goal of environmental sustainability.

In 2022, IRGC explored in more depth some emerging technologies and invited experts to describe what is being done in their domain toward the goal of the project. Papers 1 to 8 discuss specific emerging technologies and their possible applications. Papers 9 to 12 present types of instruments or approaches relevant across several domains to identify, assess and manage threats that new technologies in development could pose to environmental sustainability. The papers[4] focus on future applications or products and describe what is currently done or could be done to identify and anticipate risks earlier than conventional product assessment or regulators usually require.

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[2] IRGC is grateful to Chad M. Baum, Lucas Bergkamp, Carlos Felipe Blanco, Romain Buchs, Priscilla Caliandro, Martha Crawford, Christian Moretti, Arthur Petersen, Rainer Sachs, Christian Schwab, and Benjamin Sovacool for their contribution to writing this introduction.

[3] IRGC. (2022). Ensuring the environmental sustainability of emerging technologies. EPFL International Risk Governance Council (IRGC). See doi.org/10.5075/epfl-irgc-292410.

[4] On 27 June 2022, preliminary versions of the papers were reviewed in an expert workshop, which also included discussions around tentative cross-sectoral learnings about how ESET is being approached in various emerging technology domains.

Papers on technologies and their possible applications

[1] **Risk governance of emerging technologies: Learning from the past** (R. Sachs, Sachs Institute)
[2] **Gene drives: Environmental impacts, sustainability, and governance** (J. Kuzma, North Carolina State University)
[3] **Smart materials and safe and sustainable-by-design – a feasibility and policy analysis** (S. F. Hansen, F. Paulsen, Danish Technical University, and X. Trier, University of Copenhagen)
[4] **Ensuring the environmental sustainability of emerging technologies applications using bio-based residues** (C. Moretti, ETH Zurich)
[5] **Lithium-ion batteries for energy and mobility: ensuring the environmental sustainability of current plans** (P. Caliandro, A. Vezzini, Bern University of Applied Sciences)
[6] **Ensuring the environmental sustainability of emerging space technologies** (R. Buchs, ClearSpace)
[7] **Ensuring the environmental sustainability of emerging technologies for carbon dioxide removal** (B. Sovacool, C. M. Baum, Aarhus University)
[8] **Is cultured meat environmentally sustainable?** (C. N. Schwab, M. Boursier, EPFL)

Papers on approaches for ensuring that outcomes or emerging technologies are environmentally sustainable

[9] **Practical solutions for *ex-ante* LCA illustrated by emerging PV technologies** (S. Cucurachi, C. F. Blanco, Leiden University)
[10] **Anticipatory life cycle assessment for environmental innovation** (T. P. Seager, Arizona State University)
[11] **Liability's role in managing potential risks of environmental impacts of emerging technologies** (L. Bergkamp)
[12] **Ensuring environmental sustainability of emerging technologies – the case for applying the IRGC emerging and systemic risk governance guidelines** (R. Sachs, Sachs Institute)

This section introduces the twelve papers of the edited volume and includes: (i) a brief analysis of common themes and (ii) specific observations and learnings from each paper transferable to other domains. Together, they complement the learnings and recommendations presented in the March 2022 report[3]. Readers interested in ensuring a "better safe [and sustainable] than sorry" approach are thus referred to that report, where they can find other cross-sectoral aspects relevant to various technology domains (chapter 3), possible response strategies (chapter 4), and overarching recommendations (chapter 5).

Common themes

Certain themes are recurrent across several of the twelve papers published in this volume. We present them briefly below, indicating which papers mention them [numbers in brackets refer to papers as numbered in the list on the left side of this page].

■ Uncertainty, in the sense of lack of knowledge, is the first aspect noted in all technology domains

There are uncertainties about many aspects, including which exact future applications will be developed, the large-scale deployment of new techniques that affect the natural environment [7], or the behaviour of new materials or organisms when they are or could be released into the environment [3, 2]. Uncertainty also concerns which aspects of an emerging technology could cause risk to environmental sustainability, risk pathways, and potential impact [2]. It is often linked to an incomplete understanding of causal links [11], unavailability of data [3, 6, 7, 9], insufficient data sharing [5] or poor data quality [3], suggesting that:

PERVASIVE UNCERTAINTY

- more resources are needed for data collection [2, 10];
- currently available instruments for scientific assessment may not be able to provide the kind of data needed to assess future impacts of new technology outcomes [9];
- uncertainty assessment itself may provide valuable information to decision-makers; and
- regulatory requirements [5] and liability systems could be tuned as incentives to collect data regarding *ex-ante* assessment [11].

■ New approaches are needed for assessing risk from a future technology application

NEW APPROACHES TO ANTICIPATE RISKS

There is no robust technical approach to estimate potential risks when products are not deployed yet, and systemic consequences have not materialised. One way to address the challenge of anticipatory risk assessment is to define very broadly the boundaries of the future system being assessed to include potential effects far away from the initial cause of risk [2]. However, broadening creates additional challenges.

The following recommendations have been developed by Devos et al. for risk assessment of gene drive organisms [2] and could be transferred to other technology domains:

- "developing more practical risk assessment guidance to ensure appropriate levels of safety;
- making policy goals and regulatory decision-making criteria operational for use in risk assessment so that what constitutes harm is clearly defined;
- ensuring a more dynamic interplay between risk assessment and risk management to manage and reduce uncertainty through closely interlinked pre-release modelling and post-release monitoring;
- considering potential risks against potential benefits, and comparing them with those of alternative actions (including non-intervention) to account for a more comprehensive (management) context; and
- implementing a modular, phased approach to authorisations for incremental acceptance and management of risks and uncertainty".[5]

■ Life cycle assessment (LCA) could become an instrument of choice for assessing the impacts and risks of emerging technology products and applications

However, because of the many challenges in evaluating future environmental impacts and comparing them with alternatives [4, 9], current LCA ISO standards[6] need to be updated and extended to guide towards harmonised practices in *ex-ante* LCAs. *Ex-ante* LCA aims to model a future product or application of emerging technology and the economic system in which it will be deployed [9] and scale up manufacturing and related processes from lab/pilot scale to future large-scale production [8, 9]. *Ex-ante* LCA offers regulators, policymakers, and investors (including research funding agencies) a concise rationale for incentivising or constraining technology development projects that follow a conventional innovation model, such as the stage gate model [10].

FORWARD-LOOKING LIFE CYCLE ASSESSMENT

However, many technology developers or innovators follow a more lean and agile model, for which other types of forward-looking LCA are needed. For example, *anticipatory* LCA is a type of LCA designed to be effective under conditions of extraordinary uncertainty. It searches for research priorities that would resolve the most critical uncertainties in environmental assessment [10]. Therefore, it complements the searching nature of lean and agile innovation models, whereas *ex-ante* LCA complements the planning and execution nature of technology readiness level (TRL)/stage-gate innovation models. It questions more than tries to provide quantitative assessments. This LCA approach can be relevant to most emerging technology domains, and especially for potentially disruptive technologies [10].

■ It is not sure that environmental sustainability could ever be ensured *ex-ante*, given inherent uncertainties

IS ENSURING ENVIRONMENTAL SUSTAINABILITY A REALISTIC GOAL?

Regarding employing LCA methods to assess sustainability, as suggested by currently proposed frameworks for assessing chemicals' "safety and sustainability-by-design" (SSbD) [3], a question is whether sustainability can be 'fixed' in the same way safety (or sometimes risk) can. This is a non-trivial

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[5] Devos, Y., Mumford, J. D., Bonsall, M. B., Glandorf, D. C., & Quemada, H. D. (2021). Risk management recommendations for environmental releases of gene drive modified insects. *Biotechnology Advances*, 107807.

[6] ISO. (2006a). *ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines*. iso.org/standard/38498.html and ISO. (2006b). *ISO14040:2006 Environmental management – Life cycle assessment – Principles and framework*. iso.org/standard/37456.html

question because the concept of sustainability is multi-faceted, and its application can be relative and variable[7]. Furthermore, sustainability assessment can change over time and be subjective. For example, there is a broad consensus that electrifying transportation systems can accelerate the reduction of CO_2 emissions (climate change risk), and electric batteries are essential for that. However, without adequate large-scale plans to implement a complete life cycle approach to produce, reuse and recycle batteries in circular economies, the gains in sustainability can be significantly reduced [5].

■ Technology assessment or LCA often highlights the presence of trade-offs

Ideally, the LCA of an emerging technology outcome should also help evaluate trade-offs with other uses and among different environmental impacts [6, 7, 9]. However, trade-offs also affect non-technical aspects such as cost and expected revenue, social acceptability, business priorities, and many others that are not captured in LCAs. Furthermore, LCAs can identify these trade-offs but are not tools to resolve them. When a technology is evaluated relative to another, decisions will usually involve several options, and techniques for trade-off resolution or decision under uncertainty will have to be employed.

> IDENTIFY AND RESOLVE TRADE-OFFS

■ Decision-makers are confronted with challenges related to the substantive validity of risk evaluation

Risk evaluation concerns analysing risk assessment outcomes and asking whether a new technology's attendant risks will be acceptable, tolerable, or not. Risk evaluation is of utmost importance when there is deep uncertainty and ambiguity. It can help to determine the acceptable level of risk [2] in a specific case and directly informs the decision to authorise or regulate an activity that involves risks, or even to prohibit the development or application of new technologies in specific domains.

Scientific evidence or substantive validity of a risk assessment is often missing or inconclusive. This can be the case when outcomes of the risk assessment cannot be compared to what might potentially happen in the real world, either because large-scale deployment is not yet possible [7] or because a particular environmental release is not authorised [2].

Furthermore, even when done by scientists and other experts, risk analysis is laden with assumptions and interpretations based on values [2]. Science cannot determine whether a risk is "acceptable" in the abstract (as this requires a policy or political decision), and even scientists may have diverging views about the sustainability of new products. This is the case for example with advanced materials (especially so-called active materials), mainly because they are adaptive and gain their attractiveness precisely thanks to their ability to modify their effects when in their target environment [3]. It is also essential to recognise that matters of individual or societal preferences can (i) motivate the acceptability of new technology applications [8] even if there is no substantive validity of their environmental sustainability, (ii) discourage the adoption of a new technology even if the absence of environmental harm is proven, or (iii) trigger the use of technology even if its environmental unsustainability is proven. In other words, a particular technology outcome may be acceptable for some communities, societies, cultures or individuals, and not for others.

> INSUFFICIENT SUBSTANTIVE VALIDITY OF RISK EVALUATION

■ Methods for making the risk evaluation process more acceptable and legitimate must be adopted to improve decisions about future technology applications [2]

When substantive evidence is insufficient, notably for regulatory purposes, the question of "how to decide" becomes more prominent. In that case, the procedural validity or legitimacy of the risk evaluation (that is, how the risk evaluation is conducted) becomes even more critical than attempting to ascertain the substantive validity of a particular risk evaluation prior to deployment [2]. Decision-makers can consider establishing procedural legitimacy

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[7] The concept of sustainability has been quite well described since 1987 (Brundtland Report), adopted in the Rio Convention in 1992 and then in many international conventions. There is no ambiguity in the concept, but specific applications can become challenging and ambiguous, primarily because of differing stakeholders interpretations and objectives.

by adopting formal and standardised frameworks and processes that are deemed sufficient to provide the necessary evidence and legitimacy to support a decision regarding future technology outcomes, especially taken under deep uncertainty.

IMPROVING PROCEDURAL VALIDITY OF RISK EVALUATION

■ Robust deliberative decision mechanisms can be helpful when scientifically-informed decisions cannot be made

Despite (and because of) the complications of producing relevant information for assessing the environmental sustainability of emerging technology outcomes, it seems crucial to pay attention and devote resources to developing robust and deliberative mechanisms for decision and governance. Examples from the past have shown that inappropriate decisions based on false negatives can have severe consequences for the environment [1]. In the face of deep uncertainty and ambiguity, decision-makers should engage with stakeholders and the public who can help them identify risk endpoints of concern (which may differ based on geography or culture) and determine acceptable levels of uncertainty or risk-benefit distributions. Stakeholders and the public should also be involved in developing and examining future regulatory frameworks [2].

NEED ROBUST DELIBERATIVE DECISION-MAKING

■ A particular decision challenge exists when an emerging technology is anticipated to generate private benefits while risks will be delayed or mutualised with the public

There is a problem of misalignment of benefit and cost when decisions are made on expectations of short-term private benefits prioritised over the potential collective burden of possible long-term costs. This involves resolving or deciding about some of the trade-offs emphasised during risk evaluation.

This raises first a moral hazard problem, i.e., a lack of incentive to guard against risk because adverse consequences would only affect others, such as next generations or people in other regions. In the former case, there is a risk to prioritise new technology whose adverse effects might manifest only in the longer term. For example, if we know that a gene drive organism can help to mitigate human diseases, but ecological risks would manifest only in the future, we may be less likely to invest in prevention or control methods today, as future generations will bear the risk [2]. In the case of chemicals, this would manifest if advanced materials with considerable short-term benefits but potential — yet non-conclusively proven — adverse effects were authorised [3]. In the case of carbon dioxide removal, we may incentivise the deployment of approaches that will quickly remove CO_2, without addressing the risk of impermanence or even reversal [7].

Second, this challenge exists when risks to environmental sustainability affect common-pool resources or public goods [2]. Common-pool resources face the challenge of the tragedy of the commons [6] when risks are shared (mutualised) while benefits are privatised. There is a risk that specific, often private, interests capture the value created by technology, and sometimes a risk of technology lock-in. Stakeholders affected by the risk have no direct control over the technology and may bear a more significant share of the harm [2, 7]. When those who deploy a new technology do not bear the cost of all the adverse impacts, they might make riskier decisions than would be socially desirable. A business may not prioritise environmental sustainability unless adequate incentives and governance rules can be established and implemented [6].

PROBLEMS ALSO OCCUR WHEN BENEFITS AND RISKS DO NOT ALIGN

■ Incentives for technology developers and investors to include environmental sustainability in their preferences are much needed

Regulation and liability can provide such incentives. Technology development should be steered towards paying attention to environmental sustainability [2, 3, 5, 7]. Significant uncertainties about the outcomes of emerging technologies and their impact on the natural environment often prevent regulators from intervening and prescribing specific management measures, except if conditions are deemed to be present for implementing a precautionary approach. However, such approaches are often seen as hindering innovation, so technology developers and those who support them prefer other types of solutions, for example, based on prevention, adaptive governance or resilience building.

In parallel, a question is whether liability systems could act as incentives to generate data about potential environmental risks, thus acting as an *ex-ante* incentive to prevent environmental harm. It may be possible to change liability rules and procedures to provide better incentives, but trade-offs also need to be made here. In any case, appropriate legislative amendments would be needed to establish the legitimacy of courts to use liability systems in this direction [11].

EX-ANTE REGULATORY INCENTIVES

■ Generic capabilities can help address risks that come with emerging technologies

For example, in its guidelines for emerging risks governance[8], IRGC suggests that organisations develop four distinct capabilities [12]:

- Enhancing proactive thinking to identify future threats and opportunities. This involves creative foresight capabilities, monitoring new technology deployment's impact and risk reduction measures.
- Evaluating the organisation's willingness to bear or avoid risk (act on its risk appetite) in its future strategies. Increasing risk appetite is an option that a business may choose to develop, provided it can afford potential downsides.
- Prioritising investments in specific key emerging technologies according to their potential to alleviate existing risks, and allocating equally sufficient resources to ensuring that new risks are not created without adequate prevention and reduction.
- Fostering internal communication and building a forward-looking culture to benefit the whole organisation, which could also expand to the public.

These capacities are relevant for addressing the challenge of ensuring the environmental sustainability of emerging technology outcomes [12].

BUILDING A FORWARD-LOOKING CULTURE

■ Is the question of environmental sustainability only an afterthought in emerging technology research and development?

In some cases, yes; in others, no. Examples of the latter include space technologies and carbon dioxide removal, which are domains where long-term sustainability concerns do not appear to be always prioritised. In contrast, environmental concerns are clearly at the centre of motivations for not releasing gene drive organisms in the open environment. Also, there is rapid catch-up in domains such as chemicals, with the EC 2020 Chemicals Strategy for Sustainability[9] and its ambitious plans to implement sustainability in decision criteria and frameworks for SSbD [3], and electric batteries, with large-scale plans for reusing and recycling millions of batteries in the years to come [5].

ENSURING "BETTER SAFE AND SUSTAINABLE THAN SORRY"

Conclusion

Altogether, papers in this edited volume demonstrate that, despite many efforts underway, there are still gaps in all domains to ensure that emerging technology outcomes do not produce risks to environmental sustainability. For example, ensuring "safety and sustainability-by-design" may be very challenging for all advanced materials. Technology developers should not see risk governance as an afterthought or a burden, only to be addressed if required by regulation or public pressure. Risk governance aims to avoid, prevent or reduce risk, and thus indirectly helps realise the benefits of new technology.

A next question concerns the extent to which specific guidance can be provided to allocate incentives and responsibilities in a way that technology developers, grantmakers, investors, policymakers and others have an intrinsic interest in caring for environmental risks.

The twelve papers are summarised below, with specific takeaways.

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[8] IRGC. (2015). Guidelines for emerging risk governance: Guidance for the governance ofunfamiliar risks. EPFL International Risk Governance Council (IRGC). doi.org/10.5075/epfl-irgc-228053

[9] EC. (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Chemicals strategy for sustainability towards a toxic-free environment. eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:667:FIN

Paper 1

Learning from past examples

The first paper, written by Rainer Sachs, "Risk governance of emerging technologies: Learning from the past", reviews some examples from the past. Some technical products or applications have been abandoned after their risks to the environment were scientifically proven and recognised by stakeholders. This is the case with chlorofluorocarbons (CFCs) and large-scale biofuel production. CFCs have been used for some time without a sufficient understanding of the environmental damage they were causing. The case of liquid biofuels from agricultural products illustrates that large-scale application of known techniques can cause significant unintended impacts across system borders. Some others, like neonicotinoids, are still in use even though their environmental sustainability is contested by scientists, but farmers say they need them. In each case, Rainer Sachs notes facts and draws learnings for the risk governance of current and future emerging technologies.

Emerging technologies develop in a context of assumptions regarding expected future benefits and potential risks, and testing these assumptions. Testing is made in several stages, from early phases of laboratory experiments, during development, to small-scale experimentation in real-life conditions. Unfortunately, detrimental environmental impacts are often detected or recognised only late in the development and application phases, making risk mitigation measures complex and costly. There were early signs of adverse consequences that either were not acted upon until very late, after significant damage had occurred (ozone layer), or have not led to a complete ban or prohibition (neonicotinoids). Therefore, early risk assessment is instrumental to maximising net benefit to society.

The main types of errors in risk assessment are false positives, or type I errors, assuming that a technology is harmful, but further developments show no or insignificant harm in reality, and false negatives, or type II errors, where initial assumptions about no or acceptable potential harm turn out to be wrong. The case of type II errors is even stronger when deliberate efforts to search for potential harm do find reasons for concerns, but those are misinterpreted, not recognised or not acted upon (type III errors).

Furthermore, assessing risks in new technology is often affected by a bias towards relying upon pre-existing knowledge (data, models, methods), even if it is incomplete or inappropriate, and another bias where unfamiliar, unexpected, or even unwanted consequences of emerging technology are granted comparably little attention and resources, and are often anticipated based on bold assumptions.

In the case of CFCs, the accumulation of scientific evidence combined with public attention to the 'ozone hole' and the availability of substitutes catalysed cooperation between stakeholders towards banning the substance.

In the case of large-scale biomass production for biofuels, which many governments supported through subsidies around 2005–2012, and even mandated in the 'clean' transportation fuel mix, it is mounting evidence of adverse consequences on land use, food production, biodiversity, greenhouse gas emissions, social and other aspects, that triggered stricter regulation of biofuel production to ensure sustainability. The case of biofuels revealed the gap between initial expectations and actual outcomes in the form of unintended consequences. New technologies or applications are often introduced for a particular benefit or to achieve a specific goal. However, the benefit or goal may not realise because unintended or unanticipated consequences may arise due to deficits in risk assessment.

In the case of neonicotinoid pesticides introduced in the mid-1990s and increasingly used in agriculture, scientific evidence of harm accumulated progressively. However, due to the high political and economic stakes, the European ban in 2018 for outdoor use led to a flurry of exemptions ('emergency authorisations') at a national level. The growing observation of adverse effects on bees, in particular, has triggered an intense controversy about significance and causality among different stakeholder groups (beekeepers, environmentalists, manufacturers, scientists, and policymakers).
In public debates, scientists are judged on their position on the controversy, and scientific results are frequently misinterpreted. Conflicts of interests are still not managed in a way that satisfies all groups. Requests for exemptions on the use of neonicotinoids illustrate the principle of 'essentiality', i.e., even if detrimental to the environment, a technology can continue to be used if it is deemed 'essential' for the economy or society, and there is no substitute at a similar cost.

The three cases discussed in this paper show the presence of false negatives. CFCs were not expected to accumulate in the stratosphere, thus causing long-term effects. The growing of agricultural crops to produce biofuels to reduce fossil fuel consumption did not consider the full array of consequences in the ecological and societal systems. Risk assessment of neonicotinoids was based on inadequate methods, such as insufficient detection limits or a lack of understanding beehive system.

Learning from the past would ideally enable decision-makers to understand that, when not enough attention is paid to the downside risk of an emerging technology (countervailing risks, second-order consequences), its successful deployment may be compromised. Unfortunately, the cases of CFCs and neonicotinoids show that the industry could profit for quite some time before the substances were banned, and the industry can request exemptions if the product is deemed essential.

Specific learnings relevant to other sectors or technology domains

Generic recommendations for technology developers, industry and funders include providing sufficient resources to address *ex-ante* ignorance and uncertainty, engaging in foresight, early-warning systems and exploratory impact and risk assessment, and recognising and dealing with conflicts of interest.

In addition, obstacles or behavioural biases that can prevent learning and making risk-wise decisions must be addressed. The explicit acknowledgement and communication of what is unknown or unknowable is important and often neglected, although it is essential for effective risk governance. In particular, limitations of understanding and modelling must be made transparent.

Paper 2

Gene drives

Jennifer Kuzma's paper "Gene drives: Environmental impacts, sustainability, and governance" overviews gene-drive organisms (GDOs) and their potential impacts on sustainability and the environment, and suggests special considerations for governing associated risks.

Gene drive systems enable the genetic modification of entire populations in situ (within the ecosystem) by releasing just a few individuals of that species. Newer GDOs utilise gene editing technologies like CRISPR to bias the inheritance of genes with each generation towards 100%. Gene drives can be designed to cause the population to decline (e.g., via female killing) or be beneficial to the population (e.g., via genes that immunise against a disease). GDOs also promise to control agricultural pests with fewer pesticides, protect endangered and threatened species against pests and ecological hazards, and reduce the transmission of human and animal diseases.

However, their release in the open environment presents characteristics of emerging risks that are accompanied by significant complexity, uncertainty and ambiguity. Although gene drive systems can be designed to be limited in geography or spread, or to be reversible, it is difficult to predict the risks of environmental harm of GDOs prior to open release, and open release could cause widespread ecological impacts through complicated and sensitive ecosystems. Furthermore, unintended consequences to the environment or human health may arise from a lack of stability and efficacy of the gene drive molecular system, or from a spillover effect if the gene drive itself spreads into a nontarget population.

There are currently no approved field releases of GDOs. But there is also no agreement among gene drive developers and stakeholders about whether a moratorium on gene drive releases would be needed.

Risk analysis in this field is marked by a complex set of issues:

- Anticipatory evaluation of the risk is complex. First, problem formulation in the context of gene drives involves: identifying which endpoints must be protected (e.g., health, biodiversity, social or cultural systems, certain species, ecological services, etc.); considering pathways by which events can lead to harm; developing hypotheses about the likelihood and severity of the harm; identifying information and data needs for testing the risk hypotheses; and then developing a comprehensive risk and concern assessment plan. Second, societal impacts associated with GDOs will vary based on the type of GDO, geographical setting, governance system, social and cultural setting, ownership and power structures, and cultural and ethical principles. These factors are intertwined with each other and the socio-ecological systems into which they are deployed.
- Evaluating the substantive validity of risk assessments — where outcomes of the risk assessment are compared to what happens in reality — is not feasible prior to any novel full-scale environmental release. Therefore, the procedural validity of the risk assessment, which is how the risk assessment is conducted, becomes even more important than ascertaining the substantive validity of particular risk evaluations prior to GDO release and field data collection.
- GDOs risk analysis is laden with assumptions and interpretations based on values. For example, the endpoints that are evaluated in a risk assessment are based on what societies care about (e.g., certain species, specific natural resources, certain human illnesses, etc.). Also, uncertainty in risk analysis leads to various interpretations of the data to which we bring our own experiences, cultures, and worldviews.
- Regarding technical risk management, it is based on methods of molecular biology that can stop, recall, or reverse gene drives after release; and specific protocols for physical, reproductive, ecological and molecular barriers for biosafety.
- GDO-related risks to environmental sustainability may be characterised by moral hazard and affecting common pool resources or even public goods. Therefore, it is critical to consider communities' behavioural and value systems for managing risk through shared governance and collective action. Unfortunately, there are no globally established shared values and norms for gene drive governance, although conversations are emerging.

GDOs are developed in a field marked by significant uncertainties and large decision stakes, which suggests that legitimate and robust risk evaluation and decision methods must be used. As mentioned above, increasing procedural validity in support of decision-making is necessary. For example, the Procedurally Robust Risk Analysis Framework draws upon principles of responsible research and innovation (RRI), such as humility, procedural validity, inclusion, anticipation, and reflexivity. Also, approaches developed for “post-normal science” suggests that extensive consultation of stakeholder communities could help make sense of uncertain information and their interpretation, and draw policy implications. Democratic engagement is important for deciding what levels of risk are acceptable to affected communities.

Specific learnings from this case relevant to other sectors or technology domains

A fundamental lack of knowledge about unwanted side effects on other species and systemic causalities is generally a cause of concern.
The catastrophic risk potential is related to the complexity of ecosystems and the uncertainty of outcomes, related to temporal aspects.

In contrast to other technology domains where technologies are deployed before a sufficient understanding of their benefits and risks, the use of gene drive systems is marked by both enthusiasm about the potential to contribute to alleviating environmental and health hazards, and extreme prudence through the development of molecular control mechanisms for gene drives and staged field trial release guidance.

Every emerging technology developer would be advised to learn about how things are done in this field, as the paper provides examples of emerging conversations about global governance as well as investments in technical mechanisms to reduce risk.

Paper 3

Smart materials and safe and sustainable-by-design (SSbD)

The paper by Steffen Foss Hansen, Freja Paulsen and Xenia Trier, about "Smart materials and safe and sustainable-by-design — a feasibility and policy analysis", considers how so-called "smart materials" are — or could be — assessed and managed to ensure that their applications do not threaten environmental sustainability. The European Commission's Chemicals Strategy for Sustainability (2020c) aims to address this complex challenge, in particular through the concept of safe and sustainable-by-design (SSbD).

Chemical risks to environmental sustainability essentially cover the risk of damage to the environment that may manifest in the long term as a result of (i) unknown effects at the time of deployment (examples in some advanced materials) and/or (ii) the accumulation process, after a given material has accumulated and crossed some thresholds (examples with common pesticides) and/or (iii) a long time gap between the introduction and subsequent manifestation of consequences.

The term smart materials (a sub-group of advanced materials) is generally used for materials that obtain a new kind of functional property as a consequence of stimulation via external factors. Smart materials result from relatively new technologies or even emerging ones. Stimuli agents can be light, temperature, electricity, magnetic field, stress, pressure, pH, etc. These controlled abilities of smart materials make them particularly interesting for applications such as drug-controlled release, treatment of various diseases, biosensors, etc.

The authors examine if the frameworks and criteria currently considered for SSbD assessment are sufficient to address the specific challenges of emerging smart materials, particularly concerning environmental sustainability. In other words, will it be possible to assess smart materials on SSbD?

The SSbD concept underlines that both safety and sustainability should be addressed in the design phase — and not considered as an afterthought, e.g., when a material or product has been developed and is about to be used in the economy.

The paper compares several views and frameworks suggested for implementing the SSbD concept (JRC, CEFIC, Hauschild, ChemSec). All suggest first that the new technology design should follow certain essential principles. For example, CEFIC focuses on identifying the best alternative to existing products. Then comes the assessment of safety, and finally, an assessment of sustainability. Also, before assessing their risks and sustainability, analysts must understand the various kinds and compositions of smart materials (whether polymers, nanomaterials or micro- and nanorobots) and their unique properties when responding to specific stimulating agents during application.

The methodology proposed by JRC consists of a tiered approach, starting with applying cut-off criteria to avoid the use of the most harmful substances and substances of concern. Chemicals and materials that do not meet the initial cut-off criteria should only be allowed in uses deemed essential for society. How "essential use" is defined is subject to discussion, but it is generally understood as usage necessary for health, safety or the functioning of society, where there are no acceptable alternatives when considering the environment and health.

Safety assessment can be done with hazard and risk assessment methods. However, those have to be adapted for the 'emerging' feature of smart materials because the current methods may fail to capture the impact on environmental and health safety.

Sustainability assessment can be realised with life cycle (impact) assessment, noting though that, In order to use LCAs to evaluate environmental sustainability fully, further development of the method is needed to capture emerging features.

The authors conclude that the lack of reliable data and information about the sustainability of smart materials implies that it will not be possible to evaluate their performance concerning cut-off criteria for SSbD and subsequent safety and sustainability assessment. In particular, the lack of sufficient understanding of smart materials' long-term health and environmental impacts are significant obstacles to their deployment in non-confined environments. Their view is that it is not possible to evaluate the possible (anticipated, expected, potential) risks of smart materials to environmental sustainability (i.e., to biodiversity, ecosystems, natural resources and the climate) or indications of human health, social, ethical or other concerns that may influence the development of the technology or its uptake in industry and society. In their opinion, smart materials could, therefore, not be characterised as SSbD.

Some NGOs underline that the very concept of SSbD cannot apply to hazardous chemicals, as those are, by definition, neither safe nor sustainable to use. Because smart materials are built to change behaviour in response to external stimuli, the concept of SSbD will be challenging to implement in regulatory risk assessment.

Specific learnings from this case relevant to other sectors or technology domains

The attempt to treat sustainability as if the concept was similar to safety or risk is laudable but will meet significant obstacles regarding implementation, which must be overcome. Chemicals sustainability will be subject to different interpretations based on different business and value systems.

The interdisciplinary nature of smart materials (physics, biology, chemistry, engineering, material science and information technology) is challenging when it comes to risk assessment and governance. Therefore, holistic approaches for explorative technology assessment might be helpful when assessing smart materials and their broad applications in distinct domains.

In general, it seems evident that avoiding the use of harmful chemicals, such as substances of concern, and, when used, ensuring their potential reuse, safe disassembly, and recycling are key considerations for introducing smart materials in the economy and environment.

Paper 4

Emerging technologies applications using bio-based residues

Locally sourced bio-based residues are promising to expand the number of bio-based products produced sustainably in the EU. In "Ensuring the environmental sustainability of emerging technologies applications using bio-based residues", Christian Moretti discusses how to guide investments in future emerging technologies using bio-based residues and avoid finding out adverse environmental impacts at a late investment stage.

Bio-based residues are by-products from agriculture, the food and wood processing industries, biorefineries and bioenergy plants. The feedstock does not generate concerns about competition for food and land, is usually cheaper than dedicated crops and is locally available. Products from bio-based residues are expected to be the core of future bio-based innovation to move towards a circular economy via better valorisation of natural resources. Emerging applications include plastics from used cooking oil, fuels from potato peels, fuels from biogenic carbon emissions, and asphalts from lignin. However, environmental trade-offs might emerge when residues are (i) already highly demanded by the market for high-value applications, (ii) already sold for other lower revenue uses, or (iii) currently used by their producers (not sold). Furthermore, there is a risk that the environmental burden is shifted towards another environmental impact, e.g., higher eutrophication or toxicity than their petrochemical counterparts.

Life cycle assessment (LCA) methodology is the key tool to assess environmental impacts over the product life cycle. It is thus incorporated in various policy regulation mechanisms to incentivise bio-based products based on their environmental performance. However, bio-based residues are regularly produced from multi-output or multifunctional processes, i.e., processes yielding more than a single function or product to society. So, conducting an LCA of a product from a bio-based residue regularly requires allocating a fraction of the environmental impact to the bio-based residue. Despite the existence of ISO LCA methodology standards, modelling multifunctional processes is one of the most controversial methodological aspects in the LCA literature, with low convergence in recommendations in LCA guides of different countries and sectors. It is, therefore, not uncommon to find the life cycle environmental impact of the same bio-based residue varying from highly positive to highly negative as a consequence of adopting different multifunctionality approaches.

This paper uses several prospective LCAs as illustrative examples to discuss the environmental benefits and trade-offs of products from bio-based residues and their uncertainty caused by multifunctionality approaches. These LCAs show that the climate impact of emerging products from bio-based residues is usually much lower than that of their fossil counterparts. For example, climate change impact reductions of 30–70% can be achieved by replacing current asphalts with lignin-based asphalts and 40–62% by replacing petrochemical polypropylene (PP) with PP from used cooking oil. However, the following considerations apply:

- High climate change mitigation performance achieved by specific conversion technologies and bio-based residues cannot be generalised since it depends significantly on regional variability and the kind of energy used. Using renewable energy and green chemicals is key to achieving high climate change impact reduction.
- Bio-based residues are scarce, and many technologies compete for the same bio-based residue. Therefore, decision-makers must be careful when diverting bio-based residues from other uses, especially in the case of low-yield technologies.
- The selection of the so-called multifunctionality approach significantly affects the environmental impacts of products from less economically valuable or physically smaller streams.
- A slight change in the allocation share of the main product can significantly change the allocation share of the by-product and, consequently, its environmental impact.
- It is not trivial to evaluate and quantify the environmental sustainability of an emerging technology to convert bio-based residues before investment and production have begun.

Specific learnings from this case relevant to other sectors or technology domains

The following conclusions obtained in this case can also be valuable for other emerging technologies:

- It can be misleading to generalise conclusions obtained in any specific LCA for any specific product and wrong to transpose their outcomes into other settings.

- Key decisions are often taken based on pilot demonstrations. However, future large-scale deployment might significantly differ. Potential process design changes and size scaling effects depend on optimising process synergies and future technological learning.
- Attention is needed when diverting a scarce resource from another use which might be more environmentally attractive. A consequential LCA is the most appropriate tool to detect counterfactual impacts on the environment in these cases. However, evaluating the best use for constrained resources requires a complete understanding of the context of supply chain systems and competing markets, which may not exist until a market is created. So like in many other domains, decision-makers may see choices in terms of trade-offs, whose resolution may also need other analytical methods than LCA.
- Objectives regarding environmental impacts and economic outcomes may not align. Environmentally sustainable products generally have a (much) higher production cost than conventional products relying on (often) cheaper fossil resources for their production.

Paper 5

Lithium-ion batteries

In their paper "Lithium-ion batteries for energy and mobility: Ensuring the environmental sustainability of current plans", Priscilla Caliandro and Andrea Vezzini discuss current concerns raised by policy and industry decisions to develop large-scale plans to produce electric batteries for the mobility and energy sectors without adequate large-scale plans being made upfront for recycling, reusing or disposing of. Ultimately, this may contribute to aggravating specific environmental challenges.

Current lithium-ion batteries (LIBs) pose environmental, economic, social, legal and even ethical challenges in the different stages of the value chain. There are risks during manufacturing, using and reusing, and recycling/remanufacturing and disposal, which the paper reviews in some detail.

The main challenges for LIBs recycling are (i) separating small cells from other e-waste and (ii) current low volumes of large-format batteries that make operating plants at a scale not profitable. This calls for a business model that will enable a sustainable and circular value chain.

The paper delves into three major aspects that affect the environmental sustainability of current plans to ramp up the electrification of the individual transportation sector: the size of the battery recycling problem, ways to share information needed to process batteries into reusing and recycling, and the circularity strategy.

First, we need to scale up recycling facilities. Looking at the scale of the battery market, the expected evolution of the technology and the resources needed to achieve them, more coordination is needed between economic, environmental, social, and regulatory entities to ensure the environmental sustainability of LIBs. According to sources, the percentage of LIBs that are currently recycled ranges from 15% to 50%. Given the projection of LIBs deployment in the following years, many more additional recycling facilities will be needed. In June 2022, there were over 21 million EVs on the road globally, but by the end of the decade, this number could increase to 350 million.

Second, we need to increase the chances that every battery can be reused and recycled by making available specific information about each battery that is currently not made available by manufacturers and users. For that purpose, the Global Battery Alliance and the EC promote the "Battery Passport" as a global solution to share information and data on battery systems needed for reuse and recycling. This could enable resource efficiency across the battery life cycle while simultaneously demonstrating responsibility and sustainability to consumers. The Passport is anticipated to act as a standard-setting instrument to enhance transparency through sharing data on materials chemistry, battery origin, the state of health of the battery, or the chain of custody. It can also provide a powerful means to identify and track batteries throughout the life cycle and, hence, support the establishment of systems for life extension and end-of-life-treatment. Eventually, it can support industry marketing strategy, branding and reputation, and serve as an incentive towards the environmental sustainability of the entire industry. The Battery Passport is expected to allow for the reduction of sustainability risks and reach the following targets: (i) the reduction and/or the sustainable procurement of critical metals, (ii) the reduction of waste, (iii) an efficient manufacturing and recycling process, (iv) the exchange of data among key stakeholders to improve the economics of life extension through repair, refurbishment and recycling, and (v) the promotion of product design and technical development to facilitate disassembly for repurposing, repair and recovery of materials.

Third, LIB is an excellent candidate for circular economy practices. The EU Circular Economy Action Plan identified batteries as one of the resource-intensive sectors with a high potential for circularity to be addressed as a matter of priority. The EU created a proposal for a regulation on batteries and waste batteries oriented towards modernising the EU battery legislation to ensure the sustainability and competitiveness of the EU battery value chain. Circular economy principles can guide the sustainable management of the rising volume of end-of-life LIBs via a hierarchy of recovery pathways: reuse in less demanding applications (such as stationary energy storage) and material recovery through recycling, reducing the burden of mining raw materials. Each of these reuse pathways offers the potential to minimise the magnitude and pace of LIB waste generation while simultaneously reducing the life cycle environmental impacts of energy and vehicle storage systems.

Specific learnings from this case relevant to other sectors or technology domains

This case illustrates well the challenge of implementing circular economies and aligning manufacturing with reusing and recycling at chemicals' end-of-life. Given current plans to electrify the mobility and energy sector, it would be a mistake not to ramp up quickly on LIBs' reusing and recycling phase.

The solution proposed by the EU and other stakeholders, a "Battery Passport" designed to address one by one each of the deficiencies in the current battery life cycle, looks promising. The Passport will serve to share information and enable the implementation of reusing and recycling batteries.

Paper 6

Space technologies

In the paper "Ensuring the environmental sustainability of emerging space technologies", Romain Buchs reviews current and possible ways to ensure the environmental sustainability of emerging space technologies.

The size of activities in space is increasing dramatically, and their impacts on space and terrestrial environments are of growing concern. While stakeholders are generally more focused on the impact on the safety and security of operations, broader impacts on overall sustainability begin to raise more attention. A thorough understanding of those impacts is instrumental to informed decision-making, helping funders, developers and regulators take appropriate decisions to set space activities on a sustainable course.

It may come as a surprise to some to address the emerging concerns related to space technologies in terms of sustainability. However, near-Earth space is a finite resource and space activities have impacts across the terrestrial, atmospheric and space environments. The value of near-Earth space is increasing due to technological advances and demand for new satellite-based services on Earth, but there are no clearly established and shared rules for how to access and use space.

In many respects, the concept of environmental sustainability can be extended to space as applied in the Earth context. In this regard, it is helpful to refer to the concept of ecosystem services, i.e., the benefits that human populations directly or indirectly derive from ecosystem functions.

The concept of sustainable space activities often refers to the concerns addressed in the 2019 United Nations Guidelines for the Long-Term Sustainability of Outer Space Activities. The goal is to ensure that space activities can be performed safely and without interference so that the benefits they provide on Earth are sustained and that the outer space environment is preserved for current and future generations. The paper goes beyond this understanding and encompasses impacts from space activities on the atmosphere and the terrestrial environment.

The paper discusses the types of risks that could affect the sustainability of emerging space technologies and ways to assess and manage them. Risks to environmental sustainability from space activities include collisions with space debris, optical and radio interferences, marine pollution, atmospheric pollution, and interplanetary contamination.

Space debris is at the heart of the concerns regarding the sustainable use of outer space. These non-functional human-made objects cause a collision risk for operational spacecraft, threatening valuable assets. Congestion in near-Earth space is intensifying, especially in low Earth orbit (LEO), increasing the cost of space operations and potentially limiting future benefits. Properly managing near-Earth orbital space is thus becoming ever more crucial to protect critical infrastructure and give access to new benefits from space activities.

Methods are being developed to better assess the impacts of space activities. Life cycle assessment (LCA) is increasingly used in the space domain for assessing the ecospheric impacts. However, conventional LCA requires benchmarking to compare technologies, which is often difficult in the case of space technologies, and LCA rarely encompasses impacts beyond the atmosphere. Environmental impact assessment (EIA) is mainly used to assess impacts associated with launches and spaceports. Extensions of this tool are being developed to address the impacts of space activities on other celestial bodies. The space sector is only starting to use these tools, which are commonly used in other sectors, highlighting the sector's lateness in its consideration of the environment.

However, addressing the uncertain impacts of emerging technologies will also require other tools more capable of coping with uncertainty and a long-term perspective. Regarding space debris, in particular, the paper briefly reviews the concept of space environment capacity. This approach assumes that near-Earth orbital space is a limited shared resource and aims to indicate how much of this resource is used by space missions and objects. Similarly, a "Space Sustainability Rating" system can steer space actors towards sustainable and responsible behaviour. The paper concludes that, overall, instruments developed so far to assess the sustainability of space activities are not comprehensive and are not routinely implemented.

For spacefaring nations, national interests and security are the primary drivers of space policy. For commercial actors, the anticipated market size and business opportunities drive the risk management priorities. For example, there might be a risk that some private actors try to appropriate certain orbits (on a first-come, first-served basis). It might also be that commercial actors address the risk of loss of their satellites organised in constellation simply by creating more redundancy, which could increase the number of future debris if removal at their end-of-life is not correctly done.

Specific learnings from this case relevant to other sectors or technology domains

Technology-related risks to environmental sustainability in space are currently shared with others, but benefits are privatised. Furthermore, emerging space technologies that can create value for all might end up being captured by a few.

Like in other economic domains, specific interests thus outweigh concerns regarding the environmental impacts of space activities. For now, sustainability is only an afterthought and is not prioritised. However, the growing share of commercial applications and greater environmental consciousness can help move space sustainability higher on the political agenda.

Major threats to environmental sustainability from emerging space technology have global consequences, and will thus require a global collective response. However, due to the nature of international space law, national contexts and sovereignty must be recognised. Despite divergences among stakeholders, recognising that near-Earth is a limited shared resource with the characteristics of a common-pool resource is a stepping stone to managing it effectively globally.

Paper 7

Carbon dioxide removal (CDR)

In “Ensuring the environmental sustainability of emerging technologies for carbon dioxide removal”, Benjamin Sovacool and Chad M. Baum discuss the challenges posed by the potential deployment of emerging techniques for the large-scale removal of carbon dioxide (CO_2) from the atmosphere. Carbon dioxide removal (CDR) is likely to prove critical for stabilising and eventually reducing CO_2 atmospheric concentration in keeping with the targets of the Paris Agreement. However, while some technologies such as afforestation and soil management are already relatively mature from a development perspective, others such as biochar and direct air capture have not yet been deployed at scale. When deployed at a large scale, these techniques could substantially damage the environment or the climate itself, i.e., constituting an environmental sustainability risk.

The paper describes some potential risks of deploying four CDR techniques — bioenergy and carbon capture and storage (BECCS), direct air capture with carbon storage (DACCS), enhanced weathering, and biochar — alongside future benefits. It also emphasises the insufficient knowledge available today to inform policy decisions on the extent to which the deployment of some of these techniques should be encouraged or mandated.

BECCS involves harnessing specific energy crops or increasing forest biomass to replace fossil fuels and remove carbon dioxide by capturing and storing underground the emissions that result from burning the biomass. Because this technique is so tightly coupled to bioenergy systems, large-scale deployment could adversely affect land, water and food. However, it could also catalyse more resilient local bio-economies.

DACCS refers to capturing carbon dioxide from the air via engineering or mechanical systems, and then using solvents or other techniques to extract it before storing it underground. DACCS technology faces fundamental challenges, including high cost, energy requirements and the permanence and security of the long-term storage and sequestration of CO_2. On the other hand, DACCS could, in principle, be installed almost anywhere and would require relatively little land.

Enhanced weathering works by increasing the ability of rocks to absorb CO_2 from the atmosphere. It employs alkaline materials (such as basalt or lime), which naturally interact with carbon to draw down and provide long-term CO_2 (in the form of solid carbonate minerals). Reasons for concern include the sheer quantity of rocks that would probably be required (and mined), especially if we aim to remove multiple billions of tons annually. In addition, when done in marine environments, as is the case for ocean alkalinity enhancement, there are potential issues with how this might (adversely) impact oceans, life below water and/or water security. However, it could provide a means for helping to address the pressing problem of ocean acidification.

Biochar is a form of carbon removal that works by managing the thermal degradation (i.e., heating it) of organic material, such as tree branches or cornstalks, inside a container with no oxygen. A primary risk — one common to all carbon-removal methods reliant on biomass — is the prospect of adverse impacts on terrestrial ecosystems and land management. In particular, there is the potential for trade-offs and competition for scarce biomass resources. However, biochar could also contribute towards more carbon-rich soils, providing co-benefits for agriculture and food, and more sustainable forms of building materials.

These four CDR approaches still must be broadly considered as emerging, given that they remain at the stage of experimentation and testing and, moreover, since there is no demonstration or deployment on the scale that would be needed to reach the potential levels necessary to help reduce climate change. Each of the four techniques presents potential threats that may manifest only in the long term and remain challenging to identify clearly and assess fully, based on what we now know — even though such knowledge is crucially needed to support evidence-based decisions. However, at a high level, we know that the balance of risks and benefits will depend to some extent on how and where the techniques are applied. We also know that the complementarity and interoperability of some CDR options imply that risks may accumulate when multiple innovations are linked together in ways that improve their functionality and attain economies of scale.

The question of ensuring that emerging CDR technologies, if deployed on a large scale, would not lead to adverse consequences for environmental sustainability is complex. There are various reasons for concern, including that (i) existing instruments such as life cycle assessments are insufficient to assess and encapsulate the full range of risks that may unfold, (ii) some other potential risks may be ignored or neglected, and (iii) more sophisticated modelling, policy analysis, and even research designs capable of understanding and capturing the risk-risk trade-offs of carbon removal are missing.

Some learnings from this case relevant to other sectors or technology domains

The case of CDR-related risks to environmental sustainability indicates that deploying the most promising CDR options in terms of CO_2 removal potential would involve a diffuse collection of risks and benefits. No benefits come without some degree of countervailing risks elsewhere. No single technology is risk-free.

CDR is likely to be critical for stabilising and eventually reducing CO_2 atmospheric concentration. Therefore, the expected risks of CDR must also be compared with the risks that might come with not deploying the technology as a way to deal with climate change risks, along with benefits in terms of climate change reduction. Analysts and policymakers should recognise the difficulty in predicting risks and embracing the intersectionality and coupled nature of risks and benefits. It may even be that some CDR techniques could come to be declared ‘essential’ despite their risk. In such a scenario, the level of acceptable risk associated with CDR would be increased.

Trade-off negotiation and resolution will be at the core of decisions for the long term.

Paper 8

Cultured meat

In the paper "Is cultured meat environmentally sustainable?", Christian Nils Schwab and Marine Boursier discuss that cultured meat (also called in vitro, artificial or lab-grown meat) is presented as a promising alternative to conventional meat for consumers who seek to be more responsible towards the environment without moving to vegetarian food. Cultured meat is produced from a small tissue sample, and the cells can be taken from a living animal, so the process does not require killing animals.

Regarding environmental issues, the main anticipated advantages of cultured meat are lower greenhouse gas emissions (GHG) and reduced water consumption because much less conventional farming for livestock, ruminants in particular, will be needed. However, this can be a matter of controversy because cultured meat can impact the environment and the climate through its energy consumption, primarily electricity used during production, or through the production of the growth medium. Currently, there is no large-scale production facility.

LCA studies conducted on cultured meat are thus based on hypothetical production processes and simulation models. Attributional approaches are recommended to evaluate or compare processes or products and identify the most impacting process parameters and the technical optimisation potential. In addition, consequential approaches can be used to evaluate the societal and economic consequences. Also, prospective LCA that includes scaling-up technology application and the context in which it would apply would be very appropriate to inform decision-makers about potential environmental impacts.

Overall, most studies so far conclude that cultured meat could offer environmental gains compared to conventional meats (beef, pork, chicken) and would obviously use much less land and natural resources than conventional meat. It has a much lower carbon footprint than beef and is comparable to the global average footprints for pork and chicken when produced using conventional energy.

The paper also indicates that health and safety aspects may need to be considered even before environmental aspects, and that many other factors will influence industrial deployment, adoption, consumer choices and regulation. For example, the economic aspects of cultured meat will also determine whether the agrifood sector will find it beneficial. If conventional meat from livestock is progressively replaced with cultured meat, several services provided by livestock farming systems will be reduced or even disappear. Livestock provides essential income for rural populations, from meat, milk, eggs, wool, fibre, and leather. Current cost estimates indicate production costs above those of conventional meat. However, they could be lowered if agriculture waste could be used to produce the energy needed for cultivated meat, thus enhancing circular economies, but assuming this does not imply diverting agriculture waste from other uses. Another factor that could change the relative price of cultured vs traditional meat could be an evolution of the legal framework towards the inclusion in the consumer price of adverse externalities (True Cost Accounting for food). Finally, consumer acceptance is not established, and cultured meat is often perceived as unnatural, in contrast to so-called "vegetarian meat".

Specific learning from this case relevant to other sectors or technology domains

Regarding the specific question of what potential impact emerging technologies for cultured meat could have on environmental sustainability, researchers, technology developers, and investors would be advised to consider prospective LCAs, which will become easier to carry out as actual products become available on the market.

However, a range of other aspects than sustainability are involved in the adoption of an emerging technology.

Paper 9

Ex-ante life cycle assessment

In “Practical solutions for ex-ante LCA illustrated by emerging PV technologies”, Stefano Cucurachi and Carlos Felipe Blanco discuss strategies to address the challenges of taking an *ex-ante* approach to life cycle assessment (LCA), which is the method of choice to assess the environmental impacts of products and services that span the global economy and trigger environmental trade-offs across multiple life cycle stages and impact pathways.

For over three decades, traditional LCA studies have been widely used to guide decision-makers and consumers regarding the environmental performance of products and services. LCA studies can be used to compare environmental benefits and trade-offs between competing product systems performing a similar function, such as electricity generation, passenger transport, or food provision. A series of ISO standards (ISO 14040) formalised the use and application of LCA. However, these standards were developed with *ex-post* assessments in mind, focusing on well-defined product systems for which sufficient data and knowledge are available, given that they have already been deployed at an industrial scale.

In contrast, the recently introduced approach of *ex-ante* LCA attempts to apply LCA already in the early research and development stages of technological products and services. In this novel application, *ex-ante* LCA aims to address the methodological quandary known as the Collingridge dilemma, which postulates that impacts cannot be easily predicted until the technology is extensively developed and widely used, while control or change is difficult when the technology has become entrenched.

Written from the perspective of LCA analysts, the paper highlights the practical challenges of conducting and interpreting *ex-ante* LCAs, using case studies of emerging photovoltaic (PV) technologies. It explores — amongst other aspects — the importance of product performance optimisation during technological development, and how it is directly linked to environmental performance. It also describes the implications of process optimisations required to mass-produce an emerging technology at an industrial scale and how such optimisations can be considered in an *ex-ante* LCA.

The *ex-ante* LCA approach can be very valuable in supporting early design improvements and sound investments, providing information about potential future large-scale environmental impacts, avoiding technological lock-ins in non-desirable technologies, identifying early comparative advantages/disadvantages, and warning decision-makers about critical material and process choices in the technologies’ designs.

To be applied successfully, *ex-ante* LCA requires close collaboration between LCA analysts, technology developers and other stakeholders to overcome numerous challenges encountered in each of the LCA phases:

- **Goal and scope definition**. Identification of the functional unit and the system boundaries of the *ex-ante* study may be difficult and can be contested.
- **Life cycle inventory (LCI)**. The analyst must model manufacturing processes that are still at the lab or pilot scale and will probably change when the technology reaches the industrial scale. Information on how these lab/pilot processes will be upscaled is usually unavailable but highly relevant for LCA models. In addition to this, the recycling potential or end-of-life behaviour of the technological components and materials is difficult to anticipate.
- **Life cycle impact assessment (LCIA)**. Potential environmental impacts of new technologies are not always covered by the existing impact categories commonly used in *ex-post* LCA studies. Standard characterisation models used at the LCIA phase may not be entirely suited to assess novel chemicals/materials (e.g., microplastic and nanomaterials) and their impact pathways. As a result, the *ex-ante* LCA models will underestimate the impact scores in such cases.
- **Interpretation**. Due to significant uncertainties in forward-looking models, *ex-ante* LCA results may be prone to imprecise, inaccurate and/or ambiguous conclusions that are difficult to convey and act upon. Scenario analysis and sophisticated uncertainty and global sensitivity analysis techniques aid the analyst in stress-testing the assumptions in the system and identifying the relevant inputs in the model that are potential drivers of uncertainty.

Furthermore, the challenges listed above are encountered in the context of dynamic and rapidly evolving technology designs, giving limited time to adjust and reinterpret the models. Despite this, *ex-ante* LCA, combined with adequate screening and computational tools, can already guide decisions in the earlier phases of technology development.

Learnings from this case

Ex-ante LCA is a practical instrument adapted from standardised *ex-post* LCA that can provide support to technology developers who need to understand environmental impacts. However, the absence of process data, impact models, and uncertainty of future developments, are key obstacles which may hamper the usefulness of the *ex-ante* LCA approach. Various practical strategies are currently being developed to overcome obstacles. Currently, no strategy fully resolves the overall *ex-ante* challenge or even the specific issue it intends to tackle. However, the combined application of these strategies demonstrably provides a more robust basis for sustainable decision-making and technology appraisal.

Paper 10

Anticipatory life cycle assessment

In this paper, Thomas P. Seager discusses "Anticipatory life cycle assessment for environmental innovation". He adopts the perspective of technology developers rather than LCA analysts, and reviews the features and relevance of anticipatory LCA in contrast to conventional (ISO type) and *ex-ante* LCAs.

The principal difficulty regarding LCA for innovation is overcoming the challenge of data gaps and uncertainties with methods that steer novel technologies towards environmentally preferable outcomes. Several theoretical or methodological advances have been made, including prospective LCA, *ex-ante* LCA, anticipatory LCA, and LCA of emerging technologies. While each approach is motivated by the same problem — i.e., the difficulty of gaining environmental insight into problems before they manifest at scale — the specific goals and unique features are different. Prospective LCA aims to improve environmental forecasting. *Ex-ante* LCA aims to compare the assessment of pre-market technologies to determine expected or projected environmental gains relative to an incumbent. Anticipatory LCA aims to identify uncertainties most critical to the environment.

Any method of environmental LCA that seeks to inform questions relevant to innovation must be organised with a model of innovation in mind. The most popular model cited in the scholarship of LCA is the Technology Readiness Level (TRL) model, which presumes a linear progression from lower readiness levels to higher ones, as knowledge from research and development accumulates. This approach has been elaborated upon for private industry as "stage-gate" innovation, in which ideas are progressed through five stages of an innovation "pipeline". However, TRL fails to account for actual, messy, non-linear product development practices that are often carried out without TRL or stage-gate processes in mind. It also fails to acknowledge the significant resource constraints under which innovation often occurs, given the enormous costs of gathering complete information.

As a result, the linear TRL/stage-gate model has now been superseded in many domains and companies by agile and lean innovation models that emphasise flexibility, recursion, and minimising capital requirements. Rather than beginning with curiosity-driven basic science, the lean/agile innovation model typically starts with customer problems or market opportunities. Then, it asks what research or experiment is needed to identify ideas, possible improvements or other features that should be prioritised for the next iteration.

The lean/agile innovation model needs environmental LCA inquiry methods that are suitable for it. The most important distinction between *ex-ante* and anticipatory LCA as they are currently practised is that *ex-ante* seeks to provide answers, while anticipatory seeks to prioritise questions. The goal of anticipatory LCA is to rank-order environmental uncertainties for technology developers. Examples of questions:

Lean/agile	Anticipatory LCA
What problem is the technology solution attempting to solve?	What functional unit represents the effectiveness of the technology? What boundaries of analysis correlate to that unit?
Who has this problem?	Which stakeholders should be engaged?
What alternatives, competitors or incumbents offer solutions?	What alternatives shall be included in a comparative analysis?
What are they willing to pay for the solution?	What environmental values represent stakeholder concerns?
What is the lifetime value of customers to the business enterprise?	What environmental liabilities (e.g., end of life) might be hidden from technology developers?
How is the product or technology created & delivered?	What are the technology's thermodynamic (material & energy) requirements at each life cycle stage? How shall environmental risk assessment models/ parameters be modelled for novel materials?
What are the minimum viable features to incorporate into the next product release? What is the next set of experiments necessary to develop those features?	To what processes or parameters is environmental assessment most sensitive?

Anticipatory approaches to LCA are designed in concert with technology developers and researchers seeking to incorporate environmental considerations into new technology development. However, the required exploration of sensitivity and uncertainty is not available in standard commercial LCA platforms. The burden of custom software development is the biggest obstacle to the broader adoption of anticipatory LCA.

Learnings from this case

It seems evident that the outcome of an anticipatory LCA could be used in a decision-making process where funding agencies, technology investors in industry or grant-making organisations, and regulators are confronted with the question of having to decide on enabling, funding, or authorising an emerging technology development. This analysis suggests that continuing to explore and develop anticipatory LCA will be valuable to help identify and do an early assessment of possible environmental risks and threats to environmental sustainability embedded into emerging technologies.

However, it is too early to recommend that funding agencies and investors suggest or mandate the use of anticipatory LCA by technology developers. Nevertheless, from their perspective, formulating the guiding questions that would be asked during an anticipatory LCA process could help reveal the uncertainties embedded in the vision of the emerging technology design and possible outcomes. Anticipatory LCA offers funding agencies and other investors a basis for identifying those environmentally relevant hypotheses or research questions that are immediate, compared to those that are either purely curiosity-driven (e.g., at TRL 1) or made necessary by the TRL/stage-gate criteria approach — and may have little environmental relevance to the agile/lean innovation process that characterises today’s technology world.

Paper 11

Liability regimes

The possible "Liability's role in managing potential risks of environmental impacts of emerging technologies" is discussed by Lucas Bergkamp, who asks whether liability regimes could take a more prominent role and complement a portfolio of strategies, including regulation, to manage emerging risks of emerging technologies and novel, innovative products. For liability systems to do so, they would have to be tuned to generate adequate *ex-ante* incentives for the good governance of innovation, which they are currently not designed to do.

Regulatory approaches to managing the risks of emerging technologies can face several limitations. They generally require deep knowledge of the industries and technologies involved, which is present within the regulated industry but not necessarily in the regulatory agency. Liability systems can complement regulation when emerging technologies create uncertainty and experience with them is limited. In contrast to regulation, civil liability is a corporation's exposure to an obligation to pay compensation (or to do some action or refrain from doing some action) when the corporation breaches a duty of care under civil law. Regulation is an *ex-ante* approach that may also impose some *ex-post* obligations (e.g., an obligation to report if harm is caused), while civil liability is an *ex-post* approach (it kicks in only after there is harm or imminent harm) that ideally generates *ex-ante* incentives. Because liability law threatens to hold companies that cause harm liable, companies have incentives to reduce the risk of harm. This specific feature of liability could be harnessed to handle risks from new technologies.

In this respect, a key issue (and limitation) is data generation before and after introducing new technologies and innovative products. Civil liability law imposes a duty to investigate possible risks and disadvantages of new technologies. In theory, a technology developer or industry could be exposed to liability in two cases: if (i) data is generated and (ii) no data is generated. However, it is hard to identify in a specific case whether the risk of liability exposure is larger in the first or the second case.

In addition, there are other limitations to liability's proper functioning to this end. First, it requires damage, negligence, and a causal link, which may be hard to prove for the environmental impact of technology applications. Other limitations include the cost of lawsuits, the burden of proof and, as noted, that there may also be liability associated with the generation of data. The more remote the risks (i.e., how far into the future a possible risk will materialise), the harder it will be for the court to identify them, as causal links may be complex due to fundamental uncertainty, threshold issues, bioaccumulation, synergistic effects, etc. So-called "long tail" damage, which is characterised by a long time gap between the time of introduction of a technology and the manifestation of consequences, presents serious challenges to the liability system

Possible remedies or approaches to mitigating the limitations of liability law exist, but many will be difficult to implement. First, remedies may have a chilling effect on inventors, innovators and technology developers — the fear of exposure to potentially large claims may deter them from engaging in invention and innovation. Further, for liability to play a role in ensuring the environmental sustainability of emerging technologies, the judiciary should be both normatively and epistemically legitimised in expanding its mission.

The paper concludes that, given the self-interest of potentially liable entities and the epistemic and normative limitations of courts of law, liability law is an inherently limited instrument in managing emerging risks of emerging technologies and new products. Effective ways to eliminate some barriers to expanding liability exposure are likely to impose high costs that must be weighed carefully against their benefits. Despite these issues, the liability system can, to some extent, be adjusted to improve the management of the risks of emerging technologies, while not discouraging desirable innovation. The balance is delicate and adjustments are best made carefully and iteratively, while learning from their effects and adapting the system progressively. As a general rule, legislatures, not courts, are best placed to take the lead and make incremental changes to better equip the liability system to manage the risks of environmental impacts of emerging technologies.

Learnings from this case

Lucas Bergkamp concludes that certain conditions must be met for liability (specifically, the most common form of liability based on negligence) to work well as a system for creating *ex-ante* incentives for prevention. These conditions include that (i) the risk must be foreseeable (i.e., the causal link must be fairly precise), (ii) there must be a reasonably available option to protect against the risk (other than not engaging in the activity at all), (iii) the damage that results from the activity must be unambiguous, not inherently tied to economic and social benefits, and constitute an injury to legally protected interests, (iv) the standard of care requiring preventive measures must be knowable (i.e., identifiable) beforehand, and (v) the question presented to the court must not be a politically charged issue with which the legislature occupies itself.

In the context of ensuring the environmental sustainability of emerging technologies, the inability to anticipate long-term environmental risks is an important issue. Assessment is generally scientifically complex, tainted with significant uncertainties about causal relations, ambiguity in the interpretation of available information, and frequent conflicting interests. These problems do not disappear if liability is triggered and courts of law are called upon to make decisions. Overall, liability can make a modest but, in some cases, an important contribution to controlling the environmental sustainability risks of emerging technologies.

Paper 12

Emerging technologies as emerging or systemic risks

The final paper in this series, "Ensuring environmental sustainability of emerging technologies – the case for applying the IRGC emerging and systemic risk governance guidelines", written by Rainer Sachs, reviews IRGC's guidelines for governing emerging and systemic risks published in 2016 and 2018, respectively. It assumes that emerging technology may create emerging risks and, thus, that some of the guidelines could be useful to govern risks from future applications of emerging technologies, many of which are also pervasive or systemic.

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.

Emerging risks are either new or known risks that become apparent in new, unfamiliar, or changing context conditions.

Emerging technologies are applied in a world characterised by an increasing interconnectedness within and between complex adaptive systems, where risks can be 'systemic', i.e., they arise from the complexity of the technology itself and/or their interaction with the environment.

Due to the interconnectedness and complexity of systems, conventional risk governance approaches often reach their limits. For example, risk management by fragmenting risks into individual categories or isolated systems works well for many traditional risks but is no longer adapted to systemic risks characterised by contagion and proliferation processes (ripple effects).

The paper uses examples of emerging technologies to illustrate risk governance strategic priorities. Recommendations from IRGC guidelines suggest:

- Overcoming obstacles to the systematic consideration of early warning signals and future scenarios. 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. Explorative scenarios are particularly relevant if they can help decision-makers structure and organise the many uncertainties arising from emerging technology.
- Understanding and embracing complexity. Low predictability, limited modelling capabilities and emergence are prominent features of complex adaptive systems, which could adversely impact the long-term sustainability of the environment or the climate.
- Implementing strategies to resolve uncertainty and ambiguity. When little is and can be known about a technology that potentially has severe negative consequences, precaution-based strategies must be considered, and a large spectrum of values and beliefs must be included in risk assessments. The consultation of extended peer and stakeholder communities is necessary to understand and interpret the limits of knowledge, particular opinions that impact risk acceptability, and their influence on strategic decision-making.
- Developing 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.
- Striving for broad framing of risks and opportunities. The framing of emerging technology as a potential environmental threat may have significant strategic consequences, which should be weighed against the risk of not deploying the technology. Benefit-risk trade-offs are most often involved. In this case, it is necessary to explore and communicate expected benefits, potential exposure and vulnerability to risks across system boundaries and different time horizons. It also happens that developers of new technologies prioritise short-term private benefits over the collective burden of possible long-term costs. Like in many other domains, short- and long-term negative externalities are rarely internalised in calculating actual costs.