This paper is part of the IRGC project "Ensuring the environmental sustainability of emerging technologies".
Suggested citation: Sachs, R. (2022). Risk governance of emerging technologies: Learning from the past. In M.-V. Florin (Ed.) (2023). *Ensuring the environmental sustainability of emerging technologies* (Edited volume). Lausanne: EPFL International Risk Governance Center. DOI: 10.5075/epfl-irgc-298445

Risk governance of emerging technologies: Learning from the past

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Introduction

This paper is written in the context of EPFL International Risk Governance Center's (IRGC) project on "Ensuring the environmental sustainability of emerging technology applications" (ESET). As defined in the ESET project, emerging technologies are characterised by radical novelty, noticeable impact, relatively fast growth, coherence, uncertainty and ambiguity (Rotolo et al., 2015). The range of emerging technologies is broad, with applications in many domains.

Ensuring the environmental sustainability of an emerging technology outcome is challenging in two main dimensions. First, it is about understanding and managing the sustainability aspects of technology. Outcome and impact on the environment, both hypothetical and actual, need to be identified and mitigated. The second challenge relates to the emerging features of newly developed and deployed technology. The lack of knowledge and experience with emerging technologies makes the *ex-ante* assessment of environmental risks even more difficult.

This analysis focuses on what can be learned from past examples of technologies, substances or applications that have been used for some time without sufficient understanding of their detrimental impact on the environment. Early signs of concerns or indications of potential adverse consequences were not acted upon until very late, after significant damage had occurred. This paper reviews historical cases of new products or their application on a large scale and their risk governance from an *ex-post* perspective. The objective is to reduce the risk of repeating mistakes from the past.

Three cases are reviewed: chlorofluorocarbons (CFCs), liquid biofuels and neonicotinoids. The analysis aims to distil patterns from these past cases for improving the risk governance of current and future emerging technologies and expand the range of lessons learned in previous reviews conducted by, for example, the European Environmental Agency (EEA, 2001, 2013).

The paper starts by summarising aspects of errors and learning in the context of emerging technologies. Then, for each of the three examples, we review their development background and evolution of risk assessment and regulation process, and provide some risk governance observations. Finally, the analysis concludes with lessons to be drawn from these selected examples. They should be reflected in applying and developing risk governance approaches for emerging technologies.

1. Learning lessons – why and how?

Learning in the context of emerging technology is about forming beliefs (hypotheses) regarding potential future risks and benefits and testing these hypotheses. Most likely, testing will happen in several stages, from early phases of laboratory experiments, during development, and small-scale applications (sandboxes) to real-life applications. As observed in the past (EEA, 2001, 2013) detrimental environmental impacts are often detected or recognised only late in the development and application phases, making risk mitigation measures often complex and costly. Early assessment of risks is, therefore, instrumental.

1.1 Hypothesis testing

We briefly summarise below the most critical aspects of hypothesis testing to understand the outcomes and limitations of the process. We will need statistical terminology to make the argument as straightforward as possible. The first step in the process is the definition of a null hypothesis. The null hypothesis (H_0) is that the emerging technology under consideration does not cause harm to the environment. In the testing framework, we aim to reject this null hypothesis, i.e., we look for evidence of environmental harm. If we cannot reject H_0, we can assume that the emerging technology can be safely developed and applied within the significance level and parameters of the testing framework.

In general, there are two types of errors in hypothesis testing, which are briefly explained here:

- False positives or Type I errors occur if we reject H_0 and assume that the technology is harmful (and we either adapt or stop the development), but further research shows no or insignificant harm in reality. However, too many false positives will undoubtedly stifle innovation because technology might not be developed further based on risk concerns, which turned out to be "false alarms" *ex-post*. While this is undoubtedly a valid concern, an analysis by the EEA (2013) revealed that only a few examples of this type of error can be found for past emerging technologies.

- False negatives or Type II errors are the opposite, i.e., we do not reject H_0 and assume the technology is not harmful beyond acceptable limits, but it turns out the conclusion was wrong. This paper aims to extract lessons from past cases where technology caused harm despite prior expectations that it would not. We are mainly concerned with false negatives, where an emerging technology was deployed, and initial assumptions about no or acceptable potential harm turned out to be wrong. The overwhelming majority of past examples are false negatives, i.e., risk management and/or regulatory response was too late or too little.

There is, unfortunately, no way of minimising both errors individually, as they are not independent. Minimising Type I errors increases Type II errors and vice versa. The cost of being wrong determines the test strategy and sets the test parameters accordingly. If we could consider environmental (and societal) costs due to harmful application of technology appropriately, we would probably be more inclined towards reducing Type II errors. The concept of Safe and Sustainable by Design (SSbD) aims explicitly at reducing Type II errors right from the initial development process. We refer to a recent report from the Joint Research Centre (2022) for a comprehensive review of SSbD.[2]

Table 1 below summarises the possible outcomes of hypothesis testing.

In reality, there can even be another type of error rooted in an erroneous interpretation of the hypothesis test framework and results, sometimes called Type III error. In the hypothesis testing setting, we aim to disprove the null hypothesis, i.e., find evidence that the emerging technology does indeed cause harm to the environment. The failure to reject the null hypothesis does not prove that the null hypothesis is, in fact, true. While we can falsify H_0 for sure, it is simply impossible to prove H_0. For example, we might fail to imagine possible consequences and/or application cases and, therefore, cannot reject or even define the null hypothesis. Finite resources (time, funding, people) will also limit the search for counterevidence. In other words, the hypothesis testing framework cannot produce proof of no harm but only a plausible assumption with pre-defined target specificity. The absence of proof of harm is not equal to the proof of no harm. This needs to be reflected in the discussion and setting of test parameters ("Are our limits conservative enough?") and the communication of results with policymakers and the public.

1.2 Limitations of learning

In quite general terms, learning is about trying something new, experiencing feedback and adjusting behaviour. Moreover, learning involves mental models to project into the future possible outcomes of action in the present. In radically innovative situations, when a particular technology and its impact on the environment are hitherto unknown, this frequently amounts to the task of thinking the unthinkable. However, systematic barriers have been analysed in organisational decision-making, for example by Gowing & Langdon (2016). These barriers will ultimately contribute to Type I and Type II errors.

Table 1 | Confusion matrix

		Null hypothesis H_0 is	
		TRUE (harm not realised)	FALSE (harm realised)
Decision about null hypothesis H_0	NOT REJECT (harm not expected)	**Specificity**	**Type II error** (false negatives)
	REJECT (harm expected)	**Type I error** (false positives)	**Sensitivity**

[2] See also the paper written for the ESET project by Steffen F. Hansen, Freja Paulsen and Xenia Trier, "Smart materials and safe and sustainable-by-design — a feasibility and policy analysis" (2022).

Successful learning and designing appropriate hypotheses and testing frameworks, therefore, require addressing three classes of barriers:

1. **Complexity of the situation**. Governance of emerging technology often involves "wicked problems" (Chandran et al., 2015) from a policymaker's perspective. These types of problems:
   - are difficult to clearly define in the first place because of the complex internal relations and unclear system boundaries,
   - are challenging to frame, understand sufficiently and raise awareness so that the problem gets the attention it deserves,
   - have no clear, unambiguous solution,
   - have no clear owner or do not sit within the responsibility of a single organisation, either administration or country, due to the transboundary effects,
   - often lead to unforeseen consequences if solutions are attempted.
2. Effective mitigation of wicked problems involves radically changing **organisational structures** within which we operate and new combinations of hierarchical power, solidarity and individualism (EEA, 2013).
3. On the **individual level**, many factors can lead to systematic over or underestimation of risks and benefits. Behavioural scientists point out the impact of heuristics leading to suboptimal decisions, particularly if scientific knowledge is scarce or unavailable, as is often the case with emerging technologies. Risks that are perceived far away (e.g., in time, space, or social distance) are systematically underestimated. Table 2 below contains several examples of typical situations in which heuristics may unconsciously influence our decisions.

In addition, two strategic mistakes commonly occur in risk analysis, and these might be relevant for the risk governance of emerging technologies as well:

1. **False precision**: there is a bias towards pre-existing knowledge – data, models, methods, even if they are incomplete or inappropriate – while explicit consideration of the unknown is neglected or even ignored. Being human, we tend to focus on already well-understood and familiar aspects of the problem and the tools at hand. The precision of selected risk aspects may thus be significantly advanced, but the analysis's overall accuracy is only improved apparently at best.
2. **Reckless approximation**: unfamiliar, unexpected, or even unwanted consequences of an emerging technology are granted comparably little attention and resources, and they are often anticipated based on bold assumptions. Because of limits in knowledge, understanding and imagination we may unintentionally neglect or underrepresent risks that arise from domains outside our knowledge and expertise. Accuracy goals of the unknown are typically not made transparent and much lower than in the focus area of pre-existing knowledge.

Both effects appear quite naturally in many research contexts. For example, extensive efforts to improve understanding in a narrowly defined field may co-exist with unintentional or even deliberate ignorance of the outside world. Moreover, the necessary focus in research on specific questions, which should be answerable, at least in theory, can contribute to an imbalanced allocation of resources. Overall this can lead to a false sense of security in risk assessments of emerging technologies.

Table 2 | Example situations where heuristics may have an impact on decision-making

Observation / Situation	Effect / Heuristic at work
… others are engaged in the same activity	social proof, peer pressure
… key people have been successful in the past, also in unrelated fields	expert halo
… we focus on successful examples only and ignore the failures	availability heuristic, base rate neglect
… we have already invested in the project (time, money, resources)	sunk cost effect, prospect theory
… we have positive feelings about the idea, technology, people	affect heuristic
… the decision is consistent with past decisions and successful results	hindsight bias, escalation of commitment
… responsibility is distributed within groups (committee decisions)	risky shift, social loafing

There is a need to address the issue of lack of knowledge by, for example, systematically using concepts of uncertainty, complete ignorance and ambiguity, and describing different levels and features of uncertainty. Research helps to increase knowledge and thereby reduces epistemic uncertainty. Additionally, it is necessary to acknowledge that perfect knowledge is not possible. There will rarely be complete scientific certainty when assessing risks related to emerging technologies. Knowledge gaps are opportunities for learning and drivers for scientific progress and innovation. If everything is known there is little need for risk governance. Thus imperfect knowledge is a raison d'être for risk governance.

Risk governance of emerging technologies has specific challenges caused by the defining properties of complexity, uncertainty and ambiguity. The following case studies illustrate lessons from the past and how we can deal with these challenges. Risk management based exclusively on data and models is problematic for emerging technologies. Understanding the limits of models and knowledge is essential for further developing risk (or uncertainty) governance frameworks. Learnings can help improve decisions about the governance of emerging technologies. Good decisions come from experience, and experience may come from bad decisions. The importance of learning in the context of risk governance, particularly for foreseeing and responding to crises, has been analysed by Haldon et al. (2022). They provide past examples of how societies responded to environmental changes and either succeeded or failed in their efforts to adapt.

> "History can offer something altogether different from [scientific] rules, namely insight. The true function of insight is to inform people about the present [...] We study history in order to see more clearly into the situation in which we are called upon to act [...] The plane on which, ultimately, all problems arise is the plane of 'real' life: that to which they are referred for their solution is history."
> (Collingwood, 1939)

2. Case studies

This paper reviews analyses of three cases from the past. Chlorofluorocarbons and neonicotinoids are products that have been used for some time without a sufficient understanding of the environmental damage they were causing.The case of liquid biofuel from agricultural products illustrates that large-scale applications of known techniques can cause significant unintended impacts across system borders.

The three examples have been selected from a range of technologies and substances analysed by, for example, the EEA (2001, 2013), to distil important patterns for the governance of emerging technologies. These patterns relate notably to responding to the complete absence of knowledge, epistemic uncertainty, preparation for surprises in the sense of unexpected adverse outcomes, understanding complexity and vested interests, and communication and framing.

In each case described below, some or all of these aspects have not been adequately considered, and the technology eventually caused unintended environmental harm. Our analysis highlights learnings and conclusions from a risk governance perspective.

Each review starts with a summary of environmental impacts, as known today, after several years of large-scale deployment, and how the different stakeholder groups (technology developers, regulatory authorities, and the public) acted during the development phase, i.e., before full-scale deployment.

2.1 CFCs, the ozone layer and the Montreal Protocol

Background

Chlorofluorocarbons (CFCs) were synthesised in the late 19th century, and have been used in the industry as propellants, cleansing agents, air-conditioners, and refrigerants since the 1920s. However, the lack of comprehensive scientific knowledge about the detrimental effects in the upper atmosphere, where CFCs accumulate over time, caused inappropriate regulation of their production and use.

In 1974 scientists discovered that CFCs are causing the breakdown of ozone in the stratosphere and, consequently, the depletion of the ozone layer, which is a fundamental shield against UV radiation from the sun (Molina & Rowland, 1974). This observation triggered the systematic measurement of ozone and monitoring of CFC production. However, because of a lack of compelling scientific evidence, the chemical industry and governments did not severely restrict the production and use of CFCs. In other words, the early warnings provided by scientists in 1974 were not sufficiently acted upon.

It was not until 1985 that Farman et al. (1985) discovered the severe depletion of the ozone layer over Antarctica. First, the term "ozone hole" was coined in the media, and then the topic attracted sufficient attention and created growing public concern (Farman, 2001; IRGC, 2009).

Risk assessment & regulation process

After scientific evidence increased, the US government took measures to govern CFCs. At the same time, the industry tried to deny the existence of reputable evidence until the discovery of the Antarctic ozone hole (Farman, 2001).

A coalition of governments initiated a push for binding regulation on CFCs, followed by the United Nations Environment Programme (UNEP) in 1982. The UNEP inter-governmental negotiations led to the Vienna Convention on Protection of the Ozone Layer in 1985. The Montreal Protocol to this convention (signed in 1987 and enforced in 1989) imposed a strict timetable for phasing out ozone-depleting substances (IRGC, 2009).

The Montreal Protocol on Substances that Deplete the Ozone Layer was a ground-breaking international environmental agreement indeed. All major stakeholders were consulted during the negotiations and could cooperate effectively despite differing perspectives and interests. The Montreal Protocol was adopted more than a decade after the first discovery of harm in 1974, but only two years after the public started paying attention to the ozone hole.

The protocol adopts the principle of common but differentiated responsibility among industrialised and developing countries, thereby recognising the origin of the problem and the industrial and economic capacity to use substitutes. In addition, the industry was incentivised to develop replacement substances, thus fostering innovation. The development and availability of alternatives to CFCs was a critical enabling factor to the phasing out of CFCs.

The ozone depletion problem is on its way to being solved, and the ozone hole has started healing due to the protocol. However, the stratospheric ozone layer still bears the impacts of ozone-depleting substances because atmospheric concentrations decrease very slowly: atmospheric lifetimes of CFCs can be 50–100 years (WMO, 2006). The 2014 scientific assessment identified a stable ozone layer since 2000 and predicted a full recovery by the end of the century (WMO, 2014).

However, recent observation has identified that the ozone layer is shrinking again. In 2021, the hole was larger and deeper than 70% of ozone holes since 1979, reaching a maximum area of 24.8 million km^2 (WMO, 2022).

Risk governance observations

Before the 1970s and based on the previous 30 years of experience, risk assessment outcomes would not have raised serious concerns. CFCs have been designed to be chemically inert. Chemical inertia is generally regarded as a safety property but also leads to long environmental persistence times. Hence, the safety design of CFC involves a risk-risk trade-off: mitigation of a particular risk can lead to ancillary risks and unforeseen consequences. Because CFCs remain stable in the environment for very long times, they accumulate in a region where they eventually interact with the environment and cause harm. Practices that appear to be reasonable when introduced (in this case, when there were considerable gaps in the understanding of atmospheric processes) may later (as understanding improves) be seen to lead to a major global problem that can neither be avoided nor rapidly resolved (Farman, 2001).

The early scientific findings of Molina and Rowland in 1974 brought only limited action. It was the overall accumulation of scientific evidence combined with public attention to the ozone hole and the availability of substitutes that catalysed cooperation (Albrecht & Parker, 2019; Parson, 2003). While authoritative scientific assessments alone had been crucial in constraining the policy debates and shaping negotiations and, finally, the agreement, the key trigger was detecting the ozone hole in 1985. This finding was the outcome of systematic monitoring, which is hence of fundamental importance for the eventual adaptation of technology after deployment. Even the responsible scientists were surprised to find the extreme depletion of ozone over Antarctica, both in concentration and spatial extension (Farman, 2001) and created public awareness and pressure on policymakers.

Not only natural science was necessary, but also the social interaction between individual stakeholders. The development and implementation of the Montreal Protocol were based on an evolving community of experts. Participants developed human and social capital through networking activities, enhancing their environmental expertise and internationalism. They adopted global self-identities and established trustworthy relationships worldwide (Canan & Reichman, 2002).

A range of challenges common to international environmental agreements were successfully addressed in the process that led to the Montreal Protocol. The following aspects were instrumental and should be key objectives for multi-stakeholder discussions in general, and also regarding the environmental sustainability of emerging technologies (Albrecht & Parker, 2019):

- attract sufficient participation,
- promote compliance and manage non-compliance,
- strengthen commitments over time,
- neutralise or co-opt potential "veto players",
- make the costs of implementation affordable,
- leverage public opinion in support of the regime's goals, and
- promote the behavioural and policy changes needed to solve the problems and achieve the goals.

The negotiations, the agreement and the implementation of the Montreal Protocol demonstrate that it is feasible to trigger collective action on a global scale, even when the problems in question are difficult to understand, and even if the measurable effects of policies enacted to address the problem have relatively long time horizons before their benefits are apparent (Albrecht & Parker, 2019).

Hence, it is plausible to ask whether the approach and success of the Montreal Protocol can be transferred to other environmental challenges. There are limitations, however.

First, the availability of alternative chemical substances was a key enabler for the phase-out of CFCs. This may not be applicable elsewhere, although it is the approach taken by the EU Chemicals Strategy for Sustainability adopted in October 2020, which aims to require substituting harmful chemicals with less toxic chemicals.

Second, the political context of the 1980s was open to precautionary measures, creating a promising situation for addressing potentially disastrous global environmental threats. Since then, the political context has been claimed to have changed over the years to focus on profit, not precaution, into a "neoliberal" stance, in particular in the US, where concern for individual (and corporate) freedom is more substantial (Gareau, 2015). The EU, however, attempts to progress on both seemingly conflicting objectives simultaneously and aims to reconcile innovation and precaution. The political background must be kept in mind when one attempts to draw lessons from the CFC case and apply them to current and future situations.

2.2 Liquid biofuels in the EU

Background

Biomass has been a source of energy for millennia. Since the 1970s, government policies and programmes in many countries have led to the increased use of a broad range of biological resources as feedstocks for bioenergy. There are many different types and uses of bioenergy. This paper focuses on the case of liquid biofuels for transportation.

In the early 2000s, biofuels began to be actively considered as innovative use of existing agricultural technology that could contribute to reducing CO_2 emissions from fossil fuels. In addition, it brought an innovative change in agricultural production — mainly sugarcane, soy, maise and oil palm — leading to new products.

Three main interests drove the increasing production of biofuel (Hunsberger et al., 2014):

- **climate change mitigation** — attempts to reduce greenhouse gas (GHG) emissions raised interest in biofuels as a substitute for fossil fuels,
- **energy security** — fluctuating oil prices and uncertainty over future supplies drove interest in biofuels, and
- **economic growth in the agriculture sector.**

As a result of these interests, many governments provided financial support to producers (through subsidies) and even mandated the use of some biofuels in the transportation fuel mix. As a result, the production of biofuel crops increased rapidly.

Obviously, growing crops to produce energy also poses a threat to food production. Existing cropland is either converted to grow specific biofuel crops or so-called “flex crops” are converted into biofuel rather than food/feed. Since agricultural food production is still necessary, it may also cause an extension of agricultural land into previous non-cropland, possibly including areas with high carbon stock such as forests, wetlands and peatlands. CO_2 stored in trees and soil may be released, and biodiversity may be threatened. This process is known as indirect land-use change (ILUC).

The food versus fuel debate and growing concerns about social conflicts, e.g., changing ownerships from the local community to international organisations (land grabbing), drove a strong push for the development and implementation of sustainability criteria and frameworks (Chum et al., 2011). A promising initiative for providing frameworks for sustainable bioenergy is the Roundtable for Sustainable Bioenergy (RSB)[3]. The RSB is a multi-stakeholder organisation with members from the industry, NGOs, academia and government, with the common objective of providing global standards and certification to ensure the sustainability of all biomaterials.

Risk assessment & regulation process

Bioenergy policies, particularly biofuels, have changed rapidly and dramatically over time. We briefly summarise the regulation processes in the EU as an illustration of adapting regulation when unintended and previously unconsidered consequences surface and increase the need to act (Jordan & Moore, 2020).

In the late 1990s, the EU did not have a coherent, Europe-wide policy to promote the use of biofuels. Instead, driven by the three policy challenges mentioned above — rising GHG emissions from the transport sector, energy insecurity, and agricultural overproduction in some EU Member States — policies were designed to increase the production and use of biofuel.

The transportation sector was an obvious first target. The assumption was that greater biofuel use would not be overly disruptive from a technological perspective. In other words, the benefits of this transition were clear, and the ancillary side effects were regarded as acceptable.

The 2003 Biofuels Directive (EU, 2003) marked the EU’s first significant attempt to actively govern the production of biofuels for use in the transport sector. When it became clear that stricter regulation of biofuel production would be needed to ensure sustainability, the directive was revised in 2009, and its scope was broadened (EU, 2009). The new directive included sustainability criteria that addressed social issues related to land rights and labour and environmental considerations beyond climate, such as biodiversity.

The diversity of private biofuel certification schemes also warranted EU-level control. Continued problems with the diversity of private schemes resulted in additional procedural regulation in the 2015 ILUC Directive (Renkens, 2020) to reduce the risk of indirect land-use change and prepare for the transition towards advanced biofuels. There were limits on high ILUC-risk biofuels, bioliquids and biomass fuels with a significant expansion in land with high carbon stock. The directive also introduced an exemption from these limits for biofuels, bioliquids and biomass fuels certified as low ILUC risk.

The revised Renewable Energy Directive (EU) 2018/2001 (EU, 2018) established an overall policy for promoting and using energy from renewable sources in the EU. The current directive reinforces the sustainability criteria of bioenergy, including the negative direct impact due to ILUC.

Risk governance observations

The case of biofuels reveals the frequently observed gap between initial expectations and actual outcomes in the form of unintended consequences (e.g., ILUC, social injustice, biodiversity) and unmet targets (e.g., questionable impact on GHG reduction) (Hunsberger, 2015). This observation relates to the common lesson from studying the risk governance of emerging technologies. New technologies or applications are introduced for a particular benefit.

[3] See www.rsb.org.

However, this benefit may not realise because unintended or unanticipated consequences may arise, and deficits in risk assessment and mitigation may occur.

From a risk governance perspective, bioenergy has complex societal and environmental interactions (e.g., health, poverty, biodiversity), which may be positive or negative depending on local conditions and the design and implementation of specific projects.

Hence, biofuel regulation needs to consider broader issues like land rights, food, rural livelihoods and ecologies, not simply focusing on the benefits and apparent risks. The systemic nature of the food-energy nexus demands different forms of governance (IRGC, 2015). Early biofuel policies shared a common weakness: "by treating complex problems as though they were separate, these policies apply pressure on narrowly-defined situations in a way that does nothing to prevent problems from simply moving" (Hunsberger, 2015).

A second risk governance observation relates to the concept of "hybrid governance," an approach linking public regulation, private governance and certification arrangements (Ponte, 2014). Regulators in the EU have used a range of measures to initiate and support private biofuel certification schemes and incorporate them into their regulatory frameworks. This has led to a hybrid regime in which public and private approaches are closely intertwined (Schleifer, 2013), and a more comprehensive range of actors have become involved.

Commonly used formats of hybrid biofuel governance are "sustainability roundtables", which aim to establish democratic legitimacy as multi-stakeholder platforms.

While this is valuable in principle, it leads to even more complexity in the governance process. It allows industry-led initiatives (quicker, less democratic) to compete in the sustainability certification market (Ponte, 2014). Instead of yielding an increasingly stringent sustainability framework, the hybrid EU governance arrangements resulted in a "proliferation of relatively lax, industry-driven, sustainability standards" (Stattmann et al., 2018).

Delegating responsibility for social and environmental regulation to the private sector has led to voluntary standards and certifications. In the past, the private certification market has been largely ineffective for the following reasons: (1) rush to the minimum: producers who pursue certification tend to choose the least demanding schemes, and (2) enforcing and availability: many producers cannot or choose not to seek certification (Hunsberger, 2015).

There is also evidence that social criteria were treated as less important than production, and environmental or social practices have not improved in many places where biofuel crops are grown (Hunsberger, 2015; Hunsberger et al., 2014).

It appears easy to criticise the role of the private certification market. However, there is no realistic alternative to multi-stakeholder approaches in risk governance of emerging technologies. Hybrid governance certainly has its benefits, particularly orchestrating the different stakeholder groups with diverging interests towards a common framework. Furthermore, there are successful public-private partnerships in the form of roundtables that provide platforms for successful dialogue and cooperation, e.g., RSB. These can be instrumental in addressing uncertainty and aligning stakeholder interests for the design of public regulation.

Critical success factors in "hybrid governance" appear to be the clear allocation of responsibilities, the execution of controls, adequate resources for all stakeholders involved and transparency about individual interests. This resonates well with key factors bringing the Montreal Protocol to life, as explained in the previous section.

2.3 Neonicotinoids and honey bees

Background

Neonicotinoid pesticides (neonics) were first introduced in the mid-1990s, and their use has proliferated. They belong to the class of systemic pesticides, i.e., they can be applied to the seeds and taken up by the plant during growth (seed dressing). While losses are smaller than through aerial dispersion, only approximately 5% of the active ingredient is taken up by crop plants, and the majority disperses into the wider environment (Wood & Goulson, 2017).

Bees are critically important in the environment, sustaining biodiversity by providing essential pollination for a wide range of crops and wild plants. The Food and Agriculture Organization of the United

Nations (FAO) estimates that of the 100 crop species that provide 90% of food worldwide, 71 are pollinated by bees. Most crops grown in the EU depend on insect pollination.[4]

Several factors will impact the health of bee populations, acting in combination or separately. These include the effects of intensive agriculture and pesticide use, starvation and poor bee nutrition, viruses, attacks by pathogens and invasive species (e.g., the Varroa mite) and environmental changes (e.g., habitat fragmentation and loss). As commonly observed, complex causal relationships call for systemic risk governance.

This paper focuses on the effects of neonics on honeybees only (EEA, 2013). However, we note that the unintended effects of systemic pesticides are much broader and potentially also impact human health (Zhang & Lu, 2022).

Risk assessment & regulation process

After the introduction of neonics to the market in the 1990s, the first signs of detrimental effects on non-target organisms were observed. Beekeepers reported unusual weakening of bee numbers and colony losses, particularly in West European countries. However, at the same time, the manufacturers considered that there was no risk to honeybees under proper use, i.e., for seed-dressing.

The observation of adverse effects triggered an intense controversy about significance and causality among different stakeholder groups (beekeepers, environmentalists, manufacturers, scientists and policymakers). Scientific evidence mounted and, due to the high political and economic stakes, was discussed fiercely, both in public and within the scientific community. The positions of opposing stakeholders hardened, and science was increasingly instrumentalised. Scientific work was sometimes not judged according to its scientific merit but based on whether or not it supported the positions of some stakeholders (Maxim & van der Sluijs, 2013).

In 2012, the European Food Safety Authority (EFSA) was commissioned to produce risk assessments for three different types of neonics (clothianidin, imidacloprid and thiamethoxam) and their impact on bees. Based on the EFSA results, the EU severely restricted the use of these substances in May 2013 (EU, 2013). It prohibited the outdoor use with bee-attracting crops, including maise, oilseed rape and sunflower.

Following further assessments based on additional research and data, the EFSA published an updated risk assessment in 2018. The EC and EU Member States concluded that the EFSA findings confirm previously identified outdoor use risks. Consequently, the decision was that all outdoor use is banned, and only the use in permanent greenhouses remains possible.[5]

Several EU member states have granted so-called Emergency Authorisations for the continued use of neonicotinoids after 2013 and 2018. The assessment of validity for these authorisations is currently ongoing. A recent report from Greenpeace reveals that EU member states have issued Emergency Authorisations in more than fifty cases since 2018, sometimes even unrelated to food production, but purely for economic interests.[6] Most other countries worldwide have not restricted the use of neonics, and farmers still prefer neonics for their minimal cost and their benefits, i.e., low to moderate resistance and strong insecticidal effects.

The EC's decision to ban neonics in the EU was recently confirmed by the Court of Justice of the EU on 6 May 2021[7]. In 2018 producers of neonics filed an appeal on the ground that such a ban could have "far-reaching consequences" for the certainty and predictability of active substance approvals in the EU. However, the Court decided that the Commission was within its rights and entitled to use the recent findings of the EFSA, despite not yet being validated by EU member states.

[4] See efsa.europa.eu/en/topics/topic/bee-health.
[5] See ec.europa.eu/food/plants/pesticides/approval-active-substances/renewal-approval/neonicotinoids_en.
[6] See unearthed.greenpeace.org/2020/07/08/bees-neonicotinoids-bayer-syngenta-eu-ban-loophole/.
[7] See euractiv.com/section/agriculture-food/news/eu-court-backs-commissions-ban-on-controversial-neonicotinoid-pesticides/.

Risk governance observations

The case of neonics offers an excellent opportunity for risk governance lessons (Maxim & van der Sluijs, 2013), which broadly fall into four categories: (1) dealing with knowledge and uncertainty, (2) stakeholder management and communication, (3) structures and processes, and (4) essentiality.

1. Knowledge and uncertainty

The development of neonics and its initial risk assessment by the manufacturers happened in a sandboxed environment, as is usually done. The conclusion was that neonics do not cause harm to pollinators if used for seed dressing. The risk assessment overall results from a Type III error: no proof of harm equals proof of no harm. As it turned out, much lower detection limits were required to measure the presence of neonics in pollen and nectar. Moreover, the risk assessment methods used were initially designed for sprayed pesticides, which are inappropriate for systemic pesticides. For example, the latter also needs to consider chronic effects on bees, not only acute effects.
There was also a lack of long-term environmental and health monitoring, inadequate research into early warning and insufficient use of lay and local knowledge, e.g., beekeepers.

Scientific advice was ambiguous for the following reasons: (1) divergent data came from different sources, (2) sufficient expertise on honeybee biology was lacking and (3) there was not enough time nor rigorous criteria for evaluating the submitted information.

2. Stakeholder management and communication

Stakeholder groups had to cope with increasing mistrust and lack of access to information. Scientists were judged on their positioning in the public debate, and scientific results were frequently misinterpreted.

Stakeholder groups were (and most likely still are) lacking competencies and methods to process and communicate uncertainty and ambiguity. This led to ambiguous and inappropriate communication of scientific results.

3. Structure and processes

Conflicts of interest were not properly managed. The risk assessments were performed both by privately and publicly funded scientists. This distinction was blurred, as some publicly funded laboratories also received funding from the industry, and researchers held consulting positions in the industry. While this is not unusual given the low public funding levels, it puts scientists in a challenging position if research results are controversial.

The risk assessment process lacked clear methodological guidance on the scientific assessment of risks, regarding field vs. laboratory results, and risk measurement (lethal, sublethal effects, accumulation, chronic effects).

The available resources for risk assessment were inadequate. For illustration, the number of applications for authorisation was much too large for the number of public servants available to process the submissions (20,000 applications processed by three servants).

4. Essentiality

If a technology is deemed “essential” for the economy or society, this justifies its ongoing use even under proven detrimental impacts on the environment. The technology may be regarded as essential if there are no substitutes and expected benefits are considered to outweigh possible risks or costs. The validity of the “essentiality argument” needs careful consideration involving all stakeholders’ perspectives.

There were (and still are) diverging views regarding the essentiality of neonics among stakeholders. Industry and farmers maintain that using neonics is essential for their mandate to ensure food availability and security. Manufacturers take the number of Emergency Authorisations as an argument that farmers lack alternatives and neonics should be treated as “essential.” However, the existence of possibilities to circumvent the ban deters resources from developing viable alternatives.

Beekeepers regard the use of neonics as an existential threat to their economic existence in particular and the functioning of the ecosystem in general. So far, the EC has not adopted the view that neonics are essential chemicals.

3.

Common lessons

New technologies or applications are introduced for certain expected benefits. However, benefits may not realise, and unintended consequences may arise, which may not have been anticipated and/or adequately assessed and mitigated.

It can be helpful to consider emerging technologies in the context of transition risks (see Figure 1 below) because their dynamic structure is similar to a systemic transition (Collins et al., 2021). The analogy comes from the emerging aspects during the development phase and the disruptive potential in the application phase. Both factors can potentially lead to a system's transition. The resources allocated to define, understand and enable the technology's target benefits often outweigh the available resources to anticipate, model and mitigate the possible countervailing risks. The main argument from IRGC's previous work on transition risk governance[8] is that when not enough attention is paid to the downside risk of an emerging technology, its successful development and deployment may be compromised.

The three cases reviewed in this paper are different in the science and technology they rely on, their development and implementation paths, as well as their public reception and regulatory responses. However, some common lessons can be distilled from a risk governance perspective, which we summarise here. These factors contribute to either the success of risk governance, or its failure if they are ignored or remain neglected. The summary of lessons is meant to offer for consideration a possible set of rules for improving the risk governance of current or future emerging technologies.

Emphasize the common lessons: ensure adequate personnel (in number and competence) and financial resources to design efficient regulatory procedures for early risk identification, assessment and governance and thus reinforce their ability to manage risks effectively. Roundtables appear to give equal rights to all voices, but there is often an imbalance of power and resources. High economic interests of individual stakeholders, e.g., as evident from the neonics example, create an imbalance and make scientific risk assessments difficult.

Address ignorance and uncertainty by engaging in foresight and exploratory impact and risk

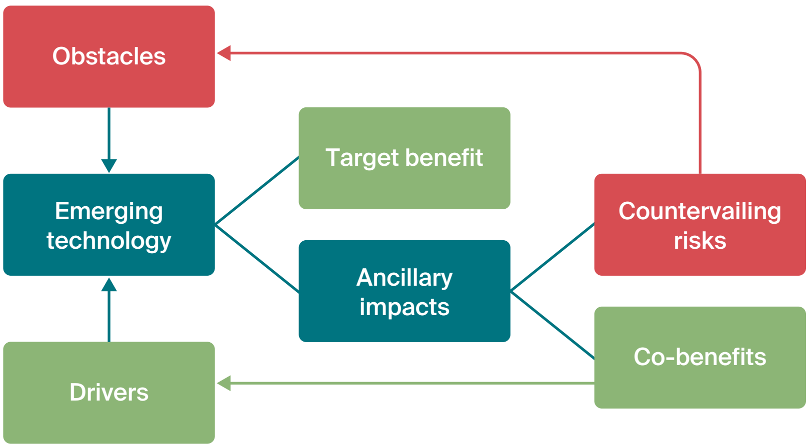

Figure 1 | Elements of the technology development and deployment process. Countervailing risks may adversely impact the target benefits if they are insufficiently addressed

[8] See epfl.ch/research/domains/irgc/concepts-and-frameworks/transition-risk/.

assessment: risk governance must contribute to identifying future properties of emerging technology and anticipating potential adverse outcomes that may arise from them. Reasonable efforts must then follow to prepare for foreseeable risks. When dealing with new technologies or applications, methods already in use for risk assessment of existing technology may not be relevant, given the new risks' specific properties and characteristics. For example, in the neonics case, risk methods were not adequate; in the CFC case, adequate methods were not even available initially. Limits of understanding, risk assessment and modelling must be made transparent: "In the end, there are few certain and enduring truths in the ecological and biological sciences, nor in the economics, psychologies, sociologies and politics that we use to govern them." (EEA, 2013)

But prepare for unexpected events, too: even the most sophisticated risk assessment will have gaps, for example due to a lack of knowledge and imagination or changing conditions of the environment where the technology is applied. In the first decades of CFC use, there were no concerns regarding adverse effects on the environment, until after more than 30 years when researchers found the first evidence of harm. The development of redundancy, capacities for adaptation and a priori development of alternative strategies and designs is of utmost importance. The case of liquid biofuels illustrates the willingness and possibility to adapt existing regulations to act upon the availability of improved knowledge and understanding.

Understand and embrace complexity: emerging technologies, as defined in this paper, have the potential to change market practices in radical ways (transformational power) and can lead to risks in different sectors (social, political, etc.) through contagion and interconnectedness. Because of their non-linear character, technological "solutions" to complex problems, e.g., the promotion of liquid biofuel production to reduce GHG emissions from the transportation sector, may lead to unintended consequences when scaled up at the system levels. Extra caution must be paid to the differences between laboratory/sandboxed environments and the real world.

Systematic monitoring for early warning signals: early warning requires proactive searching for possible risks in many different directions, e.g., by using an interdisciplinary network of specialists. Ideally, these networks have already been operational for some time, and social capital has been accumulated. While quantification of risk is beneficial and a desirable goal, the lack of possibilities, capabilities and/or capacities for quantification could be compensated by a sound qualitative assessment of the risk. For example, in the case of CFC, the implementation of systematic monitoring led to the detection of the ozone hole, which was instrumental for the Montreal Protocol.

Address conflicts of interest: the independence of science and regulation from economic and political special interests must be maintained or established, e.g., by sufficient transparency about stakeholders' involvement, their interests and financial connections. The stakeholders' vested interest in neonics contributed to the challenge of arriving at an agreeable result. Nevertheless, even with the most outstanding efforts, conflicts may persist and may not be resolved ultimately. For example, some stakeholders regard neonics as essential chemicals (allowing for possible regulation exemptions), while others consider them too harmful to be authorised. Public-private partnerships offer valuable platforms for aligning interests and sharing benefits and risks, but this type of entanglement of private and public actors in regulation (hybrid governance) has its own challenges.

Communication and framing: the debate on the risks from emerging technology applications must usually not be restricted to the scientific community alone. It must involve a broader range of actors, including the general public. Communication rules and procedures must be carefully defined and adhered to to enable a constructive debate and produce balanced solutions. What appears to be important is how the issues are framed in the first place, which parts of the problem are delegated to experts, and which parts fall under the responsibility of democratic institutions. The factors contributing to the success of the Montreal Protocol offer valuable insights into how collaboration between scientists, policymakers, industry and the public can be established. This type of collaboration can provide the foundation for constructive debates and success.

4.

Recommendations and conclusions

In this paper, we have conducted a brief review of analyses of several selected past cases. Each case was characterised by significant economic impact, uncertainty about the consequences of its use on environmental sustainability, and ambiguity concerning the interpretation of its evaluation. The objective of the review was to generate lessons and recommendations for the risk governance of current and future emerging technologies, and to provide a historical perspective relevant to IRGC's ESET project.

We started with the question of why lessons from the past are helpful and how they could be included in the learning process. We highlighted several obstacles, e.g., behavioural biases, that can prevent learning and risk-wise decisions if unaddressed. 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.

The costs of false positives (Type I error) and false negatives (Type II error) must be carefully assessed to balance benefits and risks. Technological innovation must be possible and environmental concerns must be taken seriously simultaneously.

The risk assessment showed evidence of Type II errors in all three cases of CFCs, biofuels and neonicotinoids. CFCs were not expected to accumulate in the stratosphere, thus causing long-term effects. Growing agricultural crops for producing biofuels to address, among others, GHG emission reduction targets, did not consider the total bandwidth of consequences in the ecological and societal systems. And risk assessment of neonics was based on inadequate methods, such as insufficient detection limits or a lack of understanding of beehive systems.

We believe more awareness is also needed for Type III errors: these occur if we misinterpret the results of hypothesis testing and assume there would be no harm if we cannot find evidence for it. In other words, the inability to prove harm is often understood as proof of no harm. Many reasons can cause the failure to prove harm, e.g., lack of determination and imagination of possible adverse impacts, insufficient resources, methodical deficits, etc. Education of non-scientific stakeholders and unambiguous communication can help to reduce the risk of Type III error reasoning.

The analysis concludes with a compilation of elements to inform the risk governance of current and future emerging technologies.

The common lessons result from a review of past examples, with a particular focus on the risk governance for current and future emerging technologies and expand the range of lessons compared to previous reviews, such as those from the EEA that focused on applications of the precautionary principle.

It is also worth asking which events or factors led to concrete action in the past. Table 3 below summarises key drivers that triggered risk identification, formal assessment, and management decisions. While systematic scientific research appears to be the main factor for action early in the process (risk identification), management decisions also require adequate social structures and value systems in addition to science.

Table 3 | Summary of triggers for action as observed in the past examples

Risk identification	Formal assessment	Management decision
Accidental observations	Amounting evidence	Compelling evidence
Systematic monitoring	Public concerns	Public pressure
Scientific research	Social interaction	Alternatives
Improved understanding	Multi-stakeholder platforms	Unrealised target benefits
		Political context, values, beliefs

We believe the following recommendations are instrumental in improving the sustainability of current and future emerging technologies. These are at the core of the common lessons and address scientific / technological as well as social/structural challenges in the risk governance process:

- Imagine and expect harm in seemingly unconnected systems, possibly (very) remote in time and space;
- To the extent possible, assess the total costs of Type I and Type II errors to balance necessary investments in interdisciplinary foresight and early warning;
- Be aware of the false sense of security through limits of knowledge and understanding;
- Increase transparency about stakeholder interests, allocate responsibilities, execute controls, and invest in social capital (trust) for successful conflict resolution.

Neglecting risk governance can not only cause avoidable harm to the environment, but also puts the successful implementation of the technology and its target benefits at stake.

Acknowledgements

IRGC would like to thank Benjamin D. Trump for offering comments on a first draft of this paper. The views presented in this article are those of the author and are not a consensus judgement by IRGC.

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