Routledge Handbook of Global Environmental Politics

Edited by
Paul G. Harris

Second Edition 2022

ISBN: 978-1-032-14580-8 (hbk)
ISBN: 978-0-367-69241-4 (pbk)
ISBN: 978-1-003-00887-3 (ebk)

Chapter 19

Uncertainty

Risk, technology and the future

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Funder: Australian National University

DOI: 10.4324/9781003008873-23

Routledge
Taylor & Francis Group
LONDON AND NEW YORK

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We are witnessing a "New Renaissance" of science and innovation as technologies converge to create ever more powerful platforms, products and processes (Roco and Bainbridge 2013). Rapid transformations arising from scientific discovery are not new: in modern history, the agricultural revolution, industrial revolution and the information revolution altered the fabric of society through socio-economic, political and environmental impacts (Boyden 1987; Hussey et al. 2019). Human ingenuity – driven by desperation, commercial drive, or both – spawned remarkable achievements in medicine, food, infrastructure and quality of life.

Yet, modern technologies have brought unintended and even catastrophic outcomes. The consequences of our ingenuity on the environment and human life have made names such as "Chernobyl," "Bhopal," "Fukushima" and "Exxon Valdez" synonymous with disasters. Then there are more chronic and diffuse impacts: deforestation (see Chapter 42) to biodiversity (see Chapter 41), plastics to marine systems (see Chapters 37 and 39), invasive species to ecosystem health, greenhouse gases to climate (see Chapter 32), various pollutants and wastes (see Chapters 35 and 36) to ozone depletion (see Chapter 31) and contamination of soil, air (see Chapter 30) and water (see Chapter 38). We have learned of the risks that modern innovations can bring, particularly in terms of scale and irreversibility. These events spurred developments in how we assess and manage risk and uncertainty; other events in future will too. As Rose (1991) observed, reform is "so often contingent upon an exogenous crisis."

Adverse effects aside, many technologies exist or are being developed that could address environmental problems (Hennen 1999), while others have enabled assessment techniques that reduce uncertainty through better risk analysis (Mitter and Hussey 2019) (see Table 19.1). Population growth, economic growth and consumption growth (see Chapter 17) are eroding our collective future and threaten social–ecological collapse. While addressing these underlying drivers is essential to a sustainable future, *yet more innovative technology* will also feature. The increasing demands on natural resources and vital earth systems are more complex, interconnected and urgent than ever before (see Chapters 15–17), requiring multiple channels through which solutions are sought (see the chapters in Part III of this volume). Increasingly, policymakers and regulators are in unchartered waters where they must act *promptly* but with *caution*, weighing potential benefits and harms.

DOI: 10.4324/9781003008873-23

Uncertainty with regard to environmental and human health has become more pervasive since global environmental politics emerged as a field of research in the 1980s (see Chapter 2). Some scholars describe the twenty-first century as the "era of VUCA": volatility, uncertainty, complexity and ambiguity (Hart 2020). The foci has shifted from discrete issues, to more holistic themes around human interactions with earth systems, such as the Anthropocene (see Chapter 15) and the "planetary boundaries" which define the "safe space" in which humanity must operate (Rockström et al. 2009). Throughout these developments, climate change (see Chapter 32) and the response of governments has dominated the discourse in global environmental politics, often framed around threats to food, water, energy security and the stability of global political systems (see Chapter 20 and Barnett et al. 2008). These developments have inspired new, more integrated ways of thinking toward sustainability, emphasizing the need for earth system governance (see Chapter 21), interdisciplinary and cross-sector collaboration (Brandt et al. 2013; Clark 2007; Miller 2013), systems approaches (Meadows 1999) and design thinking (Birkeland 2012; Maher et al. 2018).

The remainder of this chapter explores emerging technologies, including uncertainties around the risk and benefits they present. It looks at how regulators and policymakers manage these uncertainties and the problems they pose for existing and future governance arrangements. We begin with a sketch of significant "cutting-edge" technology platforms, their potential application to some emerging global problems and the factors that challenge governments. We examine the current treatment of uncertainty in policy and regulatory design and risk management approaches, and gaps in existing governance arrangements, and conclude with possible solutions.

Technology innovation and global challenges

Governments and industries worldwide are investing heavily in new areas of science and technology, including artificial intelligence (AI) and information technology, renewable energy and storage, nanotechnology, biotechnology, and synthetic biology (SynBio). During the first half of 2020, equity investment in SynBio increased 57 percent from the year before amidst the economic fallout of Covid-19 (Cumbers 2020), while AI's contributions to the global economy are estimated to exceed US$15.6 trillion by 2030 – more than the total of China's and India's contributions combined (Kohli 2019). From these platforms, numerous applications are emerging, spanning multiple sectors, and addressing many global challenges (see Table 19.1).

Table 19.1 Global trends, technology innovations and technology/science platforms

Global trends	
• Global climate change	• Rising populism, nationalism, geopolitical tensions
• Growing consumption of resources & waste, associated resource scarcity	• Circular economy & bioeconomy
• Declining health of ecosystems & ecosystem services	• Biodiversity loss, 6th Mass Extinction
• Covid-19 and emerging diseases	• Water scarcity, unequal access
• Energy demand and transition	• Sustainable business, policy & lifestyles
• Improving food production, nutrition	• Corporate global citizenship
• Shifting centres of economic activity	• Social life in a technological world
• Increasing wastes, pollution impacts	• Demographic change
• Prolific information sharing	• Disinformation

Technology innovations

• Vaccines	• Smart drugs	• Telehealth	• Advanced diagnostics
• Chatbots & virtual assistants	• Driverless cars & drones	• Facial and language recognition	• Immersive communications
• Bottom-up manufacturing	• Substitute materials	• Smart materials	• High-conductivity materials
• Strong, lightweight materials	• Battery storage	• Biofuels	• Eco-industrial parks
• Point-of-use energy generation	• Renewable energy	• Safer nuclear power	• Smart grids
• Intensive food production	• Resilient crops	• Crop & soil monitoring	• Targeted pesticides
• Climate control	• Better food preservation	• High value crops	• Smart irrigation
• Water desalination	• Thermal insulators	• Efficient resource extraction	• Carbon sequestration
• Automated traffic management	• Automated services & targeted marketing	• Advanced prosthetics	• At-source water purification & water separation
• Social media	• Cryptocurrencies	• Sustainable production processes	• Sorting & resource recovery technologies

Technology/science platforms

• Nanotechnology	• Synthetic biology	• Information technology	• Bio-interfaces
• Geo-engineering	• Artificial intelligence & Robotics	• Biotechnology	• Web 2.0
• Cognitive technology	• Computational chemistry & biology	• Blockchain / distributed ledger systems	• Data interfaces

Source: Adapted from Maynard and Harper (2011).

Novel solutions are emerging to address intractable environmental problems. Examples include synthetic enhancement of carbon metabolism in crops to enable net long-term carbon storage in soil (Wurtzel et al. 2019), using nanomaterials for high-power rechargeable battery systems (Xin et al. 2017) and AI-optimization of distributed energy systems (Mou 2019). More radical solutions being explored are climate geoengineering approaches such as marine cloud brightening (Ahlm et al. 2017) or solar radiation management to reduce the amount of sunlight absorbed by the atmosphere (Jinnah and Nicholson 2019), and using gene drives to eliminate invasive species by propagating lethal genes through populations (Esvelt et al. 2014). Such technologies are controversial, with justifiable concern around the ethics and implications of "messing with nature." Incomplete understanding of complex, evolving natural systems (Weis 2008) means that we cannot foresee the impacts of these technologies confidently.

Challenges of emerging technologies to traditional regulation

From a governance perspective, there are distinct features of emerging technologies and how they interface with today's globally connected society that present both old and new challenges for policymakers. Hussey et al. (2019) define these features as (1) technology splitting, (2) technology convergence, (3) new economic value and (4) regulatory divergence. Technology splitting occurs when a technology developed for one application or sector migrates to other applications and/or sectors. For example, drones originally developed for defense and surveillance are now widely used in agriculture for crop monitoring; gene technologies first applied to improve food crops are now used for a range of medicinal and industrial applications and are being advanced to create new synthetic life forms. Most pervasive are digital technologies, including the Internet and Internet-connected devices, which are now embedded in nearly every aspect of our lives.

Then there is technology convergence, the phenomenon where two or more technologies combine to create a novel application that could otherwise not occur. This differs from mere "piggybacking" in which one technology is used to improve another. For example, integrating AI systems into driverless cars ultimately produces a vehicle with the same purpose (to get from one place to another), despite its sophistication (piggybacking). In contrast, nano-encapsulated bioactive medicines and non-toxic pesticides have only been made possible through the convergence of nanotechnology and biotechnology (Mitter et al. 2017). Some believe that transformational breakthroughs will emerge in these spaces "between" platforms, creating new synergistic possibilities (see Figure 19.1).

This combination of technology convergence and splitting has led to an exponential increase in applications spanning multiple sectors and industries, where regulation and governance have struggled to keep pace. This so-called "pacing problem" has often led to decision-makers falling back on outdated policy frameworks and institutionalized ways of thinking and/or incremental changes in law and regulation that are not fit-for-purpose (Downes 2009; Dunlop 2010).

While splitting and convergence relate to a technology itself, the next two challenges relate to the world in which they are applied. The combination of low-cost inputs and new infrastructure underpin the ubiquitous nature of disruptive technologies. As demand for a new technology increases, so does the demand for the key inputs which the technology relies upon, creating *new economic value* for such commodities, sometimes where no value existed before. The most palpable example, of course, is the demand for fossil fuels following the invention of the internal combustion engine, subsequent dependence upon it, and the consequences for global warming. More recently, a growing "circular economy" movement – driven by diminishing virgin resources and increasing wastes – creates new economic value for biological and technical waste streams once destined for landfill (Stahel 2016). The advent of smart phones and laptops has seen a doubling of demand for tantalum in recent decades, and with it an increased risk of mineral conflicts in countries such as the Congo and Rwanda (Nassar 2017). Such inputs need not be tangible: data that drives AI systems, and genetic sequences used in biotechnology, have become highly sought-after commodities. Decision-makers must not only consider the impacts of the processes and applications of emerging technologies, but also of the resources underpinning them.

Finally, economic globalization (see Chapter 24) and digitalization have created highly complex supply chains and greatly diminished the role of physical borders in jurisdictional containment, enabling the rapid transfer of technologies and their diffusion to other parts of the world (the so-called speed of transfer). Consequently, regulatory divergence between

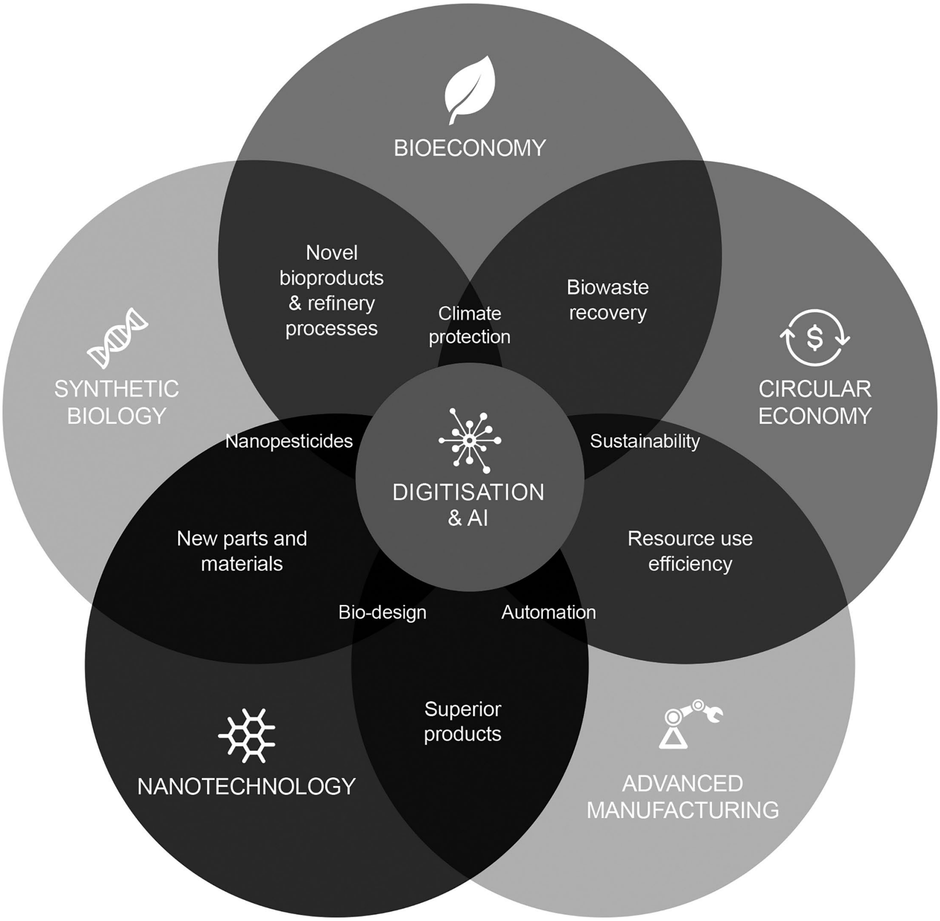

Figure 19.1 The convergence and splitting of current emerging technology and innovation platforms

Source: Adapted from Hussey et al. (2019).

jurisdictions becomes problematic, not least to ensure that environmental problems are addressed holistically, rather than merely shifted elsewhere, but also because of major shifts in *where* technology is created and by *whom*. Until recently, science and technology innovation was dominated by the United States and the EU, under well-developed risk governance regimes ranging from implementation of the precautionary principle to statutory bodies to oversee technology development and risk assessments.

Recently, the locus of technology development has shifted from west to east. China has invested heavily in science and technology and is poised to surpass US investment by 2022; it also overtook the United States in the number of patents filed in 2019 (WIPO, 2020). Likewise, South Korea is becoming a dominant player, with the largest growth in number of patents filed in 2019 and a doubling of GDP spent on R&D over the past decade (Mou 2019; WIPO 2020). Technology development is no longer exclusive to government-funded research institutes or large corporations: a college student can create a tech giant such as Facebook, while do-it-yourself biotechnology, 3D printing and accessible equipment empower individuals to develop innovations that previously required costly infrastructure and development teams (Maynard and Harper 2011). Technologies can be developed and deployed before communities and governments are aware of their potential, limiting the ability to establish safeguards before they become widespread and difficult to control (Collingridge 1980; Thierer 2018). This technology control dilemma has led to calls for a moratorium on certain emerging technologies and field experiments, for example with geoengineering (Shepherd et al. 2009: 37). But such moratoriums create not only an economic, but also a moral and ethical dilemma: if an emerging technology has potential to address a global challenge but possibly create others, should it be given the opportunity to prove itself or should risks be understood rigorously before it is applied and perhaps even developed?

Combined, these features create immense pressure on both the scientific community to rapidly identify and assess risks, and on decision-makers to weigh an abundance of new information and countervailing risks to develop appropriate, timely responses. The end result can be such that risk assessments and policy decisions fail to integrate across policy domains and jurisdictions, or the uptake of technology that proliferates ahead of regulation (Hussey and Pittock 2012). These developments have important implications for how risks and uncertainty are assessed and managed in the context of global environmental politics, not least because rigorous risk management requires a high degree of institutional capacity, but also because it reflects societal values.

Risk management and the treatment of uncertainty

Risk assessments are the primary tools used to assess the level of risk and potential harms posed by new technologies. The objectives are twofold: to determine whether a new process or product should be accepted for commercial release; and to determine the level of regulatory scrutiny (if any) required. The latter helps to ensure that regulatory resources are prioritized and deployed efficiently, and that control measures are appropriate to the level of risk (McHughen 2016). The assessment process involves systematic identification and analysis of risks, including the likelihood of occurrence and level of impact, followed by a *risk evaluation* to appraise the level of tolerable risk (see Figure 19.2). The scope and issues covered in a risk assessment are often subjective and shaped by values and politics (Cothern 2019; Bond et al. 2001; Gibson et al. 2005; Partidário and Clark 2000; Russell et al. 2011). Assessments may consider risks to the environment, human and/or animal health and safety, and/or other social or economic impacts, at a variety of scales. There are also risks in not realizing positive

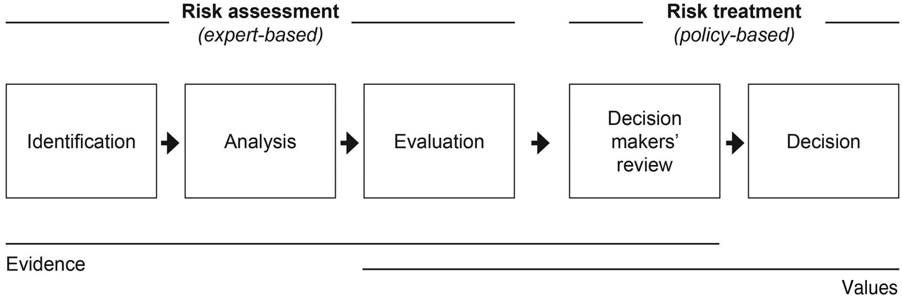

Figure 19.2 Risk management and decision-making process
Source: Adapted from Aven (2016); see also Hansson and Aven (2014).

outcomes (opportunities), particularly for environmental concerns where the risk of doing nothing could be more detrimental (e.g., action on climate change).

Then there are risks related to uncertainty, which is distinguishable from risk itself and is the subject of several examinations (see Cothern 2019; Dovers and Handmer 1995; Hansson and Aven 2014; Hoffman and Hammonds 1994; Peel 2006). Here, we use the definitions of Petersen (2006: 3): "Risk describes situations where there is uncertainty about which outcome will eventuate, but the range of all possible events is known and plausible probabilities can be assigned to each and every possible event". With uncertainty, outcomes are "known but there is insufficient information to permit objective probabilities to be assigned ... Ignorance (or radical uncertainty) is where objective (or sometimes even subjective) probabilities cannot be assigned to outcomes and the full range of possible events cannot be identified".

Uncertainty around emerging technologies arises from many factors. First, there is uncertainty about the consequences of a technology itself: how it might converge with other technologies or split across sectors, how it might be used or misused, unknown harms to environmental or human health, unintended benefits, whether adverse effects may be direct, indirect and/or cumulative, and when such impacts could become evident. Second, there is uncertainty about the nature of the world in which those technologies will be deployed now and in the future (Rip 2006), including social values, changes in the efficacy of the assessment and regulatory regime over time, or a changing operating environment because of demographic, geopolitical, climate, economic or other technological changes. Third, there are knowledge gaps regarding natural processes and phenomena, particularly feedbacks from human activities for which no precedents exist. Because of such complexity, the impacts of emerging technology on the environment often extend to radical uncertainty as we cannot foresee how their application may evolve.

The precautionary principle is a key principle used to deal with uncertainty where there is incomplete information or inconclusive evidence and where potential threats are irreversible, unknown or difficult to estimate (Fisher 2007). Its intention is not to provide a final decision, but rather to emphasize delayed decision-making and to proceed with caution until further knowledge is gained (McHughen 2016). Originally conceived for environmental protection, the principle's scope has extended to human health and safety, following high-profile regulatory failures in the 1980s. Such events, notably the BSE ("mad cow" disease) and dioxin crises, led to greater public scrutiny and fear of food and safety issues, and a general decline in trust of science and government (Anyshchenko and Yarnold 2020). Various formulations of the precautionary principle have been incorporated into international agreements including the Convention on Biological Diversity 1992, and the Framework Convention on Climate Change 1992, and in national law and policy (Peterson 2006). One of the earliest conceptions is found under Principle 15 of the UN Rio Declaration on Environment and Development, which states that "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (United Nations 1992).

There is large and contested literature on how the precautionary principle is defined, how it should inform law and policy, and how it should be applied (Fisher et al. 2006). On the premise that it is impossible to eliminate uncertainty, some have argued that the principle is a political construct used to skew public sentiment, rather than one based on science (McHughen 2016). Other discourse relates to its interpretation, including the "strength" of the principle in terms of assigning where the burden-of-proof lies. "Weak" versions put the onus on those advocating precaution to justify such precaution, while "strong" versions place the burden-of-proof on those advocating that the processes will not cause harm. Proponents of "strong" use argue that those introducing a technology generally have more power than those who oppose it (e.g., a multinational in support of a new GM crop versus local farmers opposing it), and must demonstrate its safety to mitigate the power imbalance. Such interpretations have led to regulatory divergence in the approaches taken by jurisdictions (Aldy and Kip Viscusi 2014), even sparking a trade conflict between the United States and the EU over GM crops and food products (Anyshchenko and Yarnold 2020). A further debate concerns vagueness in how the precautionary principle should be applied, leading to a lack of consistencies in precautionary approaches taken toward assessment and approval methods and processes (Dovers 2006; Russell et al. 2011).

While such issues are not easily resolved, one thing is certain: the elimination of all risk and uncertainty is not only impractical, but fundamentally impossible (Stahl, et al. 2003). The question is how to manage risk at a level deemed acceptable? The scientific, policy and political difficulty lies in defining what level of risk is socially acceptable, and how that level is defined. Risk assessments do not provide society and policymakers with "yes/no" answers: the analysis is scientific, but the evaluation and management is subjective (see Figure 19.2). Even prior to risk analysis, subjective decisions are made as to the scope of impacts to be assessed, the thresholds that define the "tolerable" level of risk, the standards of proof required, and the triggers used to determine whether regulatory scrutiny is required (Dovers 2006). A crucial point emerges: uncertainty and risk are value-laden and thus not reducible to simple metrics. Social, scientific, and political arguments over technologies consider impacts beyond the purpose of the technology. They may be founded on different perspectives on the role of science, how much care is afforded to future generations, and whether nature is valued for its own sake. Risk and uncertainty are not simply objective; they are socially constructed and negotiated through politics (Handmer and Dovers 2013; Smithson 1989).

Values, risk perception and attitudes toward technology

Attitudes and perceptions of risk and uncertainty vary widely (Bammer and Smithson 2008; Sjoberg 1979). Different experts, industries, communities and political groups perceive risk differently depending on the technology and its context. Often, those deciding on acceptable risk are not at risk themselves, which may lead to poor outcomes for those that are. Many factors influence technology risk perception, including trust in science, corporations and governments, proximity to the site of application, visibility and/or familiarity of the technology, and one's understanding of the technology. For example, when asked about perceived health impacts of living near wind turbines, those living near them were half as likely to be concerned as those who did not (Baxter et al. 2013). These issues characterize perceptions of many of the technologies listed in Table 19.1, which are shaped by the media, scientists and politicians.

Trust in science and politics has shifted recently and significantly. The role of new media in shaping societal perceptions challenges technology regulation, nationally and internationally (see Rae 2020). A combination of new, expanding information and communication technologies (e.g., social media, smartphones) and the rise of populist political movements and conspiracy theorists have polarized attitudes and popularized opposition to some scientific facts and/or official policy directions. Segments of society have become resistant to rational argument or evidence, well beyond the healthy critical stance required for scrutiny and accountability, as witnessed in climate denialism (see Chapter 32), "anti-vaxxers" (those opposed to vaccinations) and conspiracies surrounding Covid-19 (see, e.g., Gidron and Hall

2017; Kennedy 2019). For risk management, these shifts may be passing or remain marginal, or they may prelude larger moves in social values.

The international response to the Covid-19 pandemic has increased the visibility and arguably the recognized value of well-established assessment institutions and processes. Whether this global visibility will strengthen or weaken acceptance of scientific knowledge and procedures in assessing efficacy and safety remains to be seen.

Prospects for fostering responsible technologies and innovation

Summarizing previous sections, challenges in assessing risks and uncertainties surrounding technologies are complicated by the following, often shared characteristics:

- Risks may be direct, indirect and/or cumulative, and can occur over the long term.
- Perceptions of risk and uncertainty vary widely.
- Applications often spread across multiple sectors and sources of scientific discovery.
- Technological change often outpaces regulation and policy.
- The impacts of a technology may manifest at a distance from where it was developed or first applied.

These characteristics apply to traditional and emergent technologies, and the extent to which risks will be captured by existing regimes depends on governance and institutional regimes. It is clear, however, that the technologies emerging today, and the world into which they are emerging, are different from earlier periods.

To provide robust institutional arrangements and regulatory systems that can keep pace with sweeping technological advancements in the complex world we live in, we must consider: what governance mechanisms currently exist? What suite of approaches to take? And when to regulate, review and revise? These questions require a holistic, systems-based understanding of the technology's processes, applications and supply chains; more proactive, iterative and adaptive tools; and a governance regime that provides appropriate oversight to protect the environment and society without unnecessarily stifling innovation. What might the key elements of such a governance regime be?

In considering options for governing environmental impacts of technology, it is important to consider both *explicit* and *implicit* forms of governance. Explicit governance refers to specific initiatives which are enacted by those with authority to do so, such as formal policy, regulation and law, and publicly funded reviews of emerging technologies by governments or politically neutral agencies. In contrast, implicit governance refers to when other (nongovernment) components of the social/political/economic system act in a way which contributes to governing technology, without necessarily having the authority or intent to do so. This may include voluntary initiatives, market-based mechanisms, organizational culture (Rip 2006: 280), and third-party certification schemes. Applying a suite of complementary explicit and implicit governance mechanisms can help to navigate uncertainty and adapt more rapidly to evolving technology. Some overarching principles and approaches are summarized below.

Anticipatory governance

Anticipatory governance is a broad concept related to managing uncertain events of the future in the present through mechanisms that build adaptive capacity and preparedness.

Anticipatory governance features heavily as an approach to address the rapid transformations of emerging technologies and their consequences to environmental, social and economic systems, promoted widely in the disciplines of sustainability science, climate adaptation and resilience, environmental governance, national security and responsible innovation. A critical analysis of anticipatory governance and related themes by Muiderman et al. (2020) categorized perspectives based on three elements: conceptions of the future (as being probable, plausible, pluralistic or performative); implications for governance and policy in the present (planning, building adaptive capacity, mobilizing diverse stakeholders, or interrogation of existing regimes); and the ultimate purpose of employing anticipatory governance (to reduce future risks, to reflexively navigate uncertain futures, to co-create new futures or to identify implications of current political systems). Critical features of the tools employed focus on foresight, adaptive regulation, stakeholder engagement and policy integration. These are explored further below.

Environmental policy integration

Traditionally, governance processes manage the complexity of society by dividing it into discrete departments and sectors, and applying policy and regulation within those. This can be effective for discrete challenges, but is inadequate for others. It is particularly emerging technologies that split and impact across multiple sectors, stakeholder groups, and generations. One way to overcome regulatory silos is to integrate environmental policy into non-environmental policy areas, as well as into governments' fiscal protocols. This integration can happen at any level of government from whole-of-government policy to specific issues. An example is integrating the impacts of medicines in wastewater effluent on biodiversity and ecosystems into US FDA approval processes (Jordan and Lenschow 2010). Integrated approaches to policy are being applied to sustainability and climate change, and provide a valuable precedent for governing emerging technologies with broad reach such as AI and gene editing.

Adaptive regulation

The traditional approach to the development of new regulation often occurs over several years. New rules are discussed and drafted; the draft is made available for public comment; feedback is reviewed and integrated into the framework; and finally, new regulations are delivered. By the time regulations are implemented, they are often outdated by technology developments and lengthy time frames often deter reviews and reforms needed to address future regulatory gaps. Eggers et al. (2018) suggest shifting from this "regulate once and forget" approach to one based on early and frequent iterative trial-learn-feedback loops integrated with co-design and deep engagement with industry and experts.

One adaptive approach is a regulatory sandbox, which enables a technology to be deployed in the world but within a controlled environment to test products, services and business models arising from new technologies. Sandboxes have been used in the finance sector, by allowing firms to test out payment transfers with cryptocurrencies, with assurances made to a select number of participating clients (Allen 2019). The United States has recently given approval for a regulatory sandbox toward unmanned aerial navigation (Eggers et al. 2018). Of course, tangible, and often irreversible environmental and human health effects require greater containment efforts for such sandboxes, which at times may be inappropriate.

Collaborative design and multi-stakeholder engagement

Technologies impact a wide range of people across society and future generations. To ensure they bring the most good for the most people, the divergent yet legitimate perspectives of various stakeholders must be comprehensively considered to formulate the best approach of technology risk management and to build trust in how they are being used (Peel 2006: 203). Democratic principles instruct that many different groups should contribute to how these technologies are governed. Regulators can benefit from multi-stakeholder engagement, for example by reducing the economic costs associated with regulatory divergence and the risks of potential failures through various types of multi-stakeholder collaboration.

Internationally, coordination between nations through formal agreements can improve regulation of Internet-based technologies, international trade and geographically complex supply chains. Agreements might be to share information between regulators or develop processes to address different regulatory requirements. Intergovernmental and transnational institutions could play a key role in facilitating such agreements, paving the way for standard frameworks and guidelines (Eggers et al. 2018).

Policy laboratories are becoming a popular tool for regulatory co-design (Olejniczak et al. 2020). They foster multiple perspectives to challenges and solutions. This can reduce silos when developing regulation by involving stakeholders from research, corporations, industry bodies, government agencies and communities. When co-designing policy and regulation, care must be taken to manage conflicts of interest and the differing social power of stakeholders through transparency and public accountability. To engage meaningfully, individuals must understand the risks and benefits of new technologies and governments must, in turn, understand their attitudes and concerns. Such feedback enables government to prioritize the areas where technologies are most needed, and reduces the risk of investing in technologies that people do not want or outright oppose.

Fit-for-purpose and well-targeted regulation

To be effective in managing risk and uncertainty, regulation and policy responses must "fit" the characteristics of emerging technologies, rather than apply a one-size-fits-all strategy or extend outdated legacy mechanisms. For example, waste streams such as fly ash, glass, tires and plastics provide cheap and sustainable alternatives for construction and road materials, but require new or reformed construction standards and codes to implement them at scale.

Given the complexity of supply chains and range of impacts that emerging technologies can have on society and the environment, it can be difficult to identify precisely which part of the process is most suited for regulatory measures. The temptation for governments might be to impose risk assessments at some or all stages of that supply chain, but that is a temptation that must be avoided for two reasons: first, the innovation supply chain is more complicated and dynamic than ever before and more assessments are likely to add confusion where clarity is important; and second, the imposition of more assessments imposes unwelcome constraints on competitiveness and potentially on trade (Botterill and Daugbjerg 2011; Hussey and Kenyon 2011). Regulation is most important for components of the technology supply chain and its application which pose greatest risk on the environment. Where supply chains are complex, a whole-of-systems perspective is important to identify these key points of risk and developing harmonious and streamlined regulation. State-based regulation presents a challenge for international trade (see Chapter 24), imposing impediments to trade and investment and altering the competitive position of firms.

While recognizing that regulation is itself a public good, and that the uncertainty and risk surrounding new technologies demands appropriate regulatory oversight, there is a need to find ways of regulating scientific discoveries without unnecessarily stifling them. One relatively urgent need is to achieve as much harmony within and between countries as possible, thus reducing regulatory divergences, administrative redundancy, and barriers to trade and consumer welfare (Hussey and Kenyon 2011). However, this should not lead to the "lowest common denominator" in regulation, if we are to avoid further environmental catastrophes.

Market-based mechanisms and third-party certification

The fast-paced, geographically and temporally disconnected nature of technology research and development means the state is limited in how much oversight it can provide. From the 1990s onwards, in parallel with the institutionalization of the precautionary approach, disappointment with the success of traditional command and control regulation to manage environmental externalities saw the emergence of so-called second- and third-generation environmental policy (see Jordan et al. 2003; Knill and Lenschow 2003; Lenschow 2002). Including policy instruments such as market-based mechanisms, voluntary initiatives and third-party certification schemes, the global environmental politics literature is replete with studies on the efficacy of such instruments in mitigating environmental impacts. Voluntary initiatives from science and industry sectors seek to place checks and balances on their own research. These may include eco-labeling and third-party certification which provide a competitive advantage to firms with more sustainable products; moratoriums on particularly sensitive areas of research; or extensive, government-funded voluntary initiatives to examine the potential risks of a technology (Rip 2006). Initiatives from industry can complement traditional forms of governance, but may also postpone much-needed regulation. A narrow industry framing of risk may exclude important perspectives and issues which, as we have seen, are needed to fully comprehend a technology's impact on society and the environment across time.

Prioritizing technology for environmental and human good

Thus far, we have discussed prospects for governing uncertain environmental impacts of technology while taking the types of technology being developed as a given. However, there is a substantial disconnect between the problems that most need to be fixed and the technologies being developed. Notwithstanding extraordinary advancements made in medical research, problems of hunger, poverty and disease endure as environmental problems escalate, in contrast to the extraordinary proliferation of technological innovations such as smart phones and high-definition television (Bozeman et al. 2011). Technology development may not align with the types and scale of challenges we face. Policy instruments can play an important role in addressing this market failure by incorporating the full cost of environmental externalities into markets, removing subsidies to polluting industries, and providing incentives for responsible innovators. This also prompts questions such as should technologies specifically designed to address significant global challenges (like climate change) be afforded less restrictive regulation than those providing less critical benefits (such as entertainment technology)?

Conclusion

Governments are key in assessing potential risks, defining oversight structures and systems, promoting transparency, protecting citizens, informing the public and steering responsible development of technologies. The theme of stronger, more integrated but also more objective institutions is reiterated in the academic literature, which reinforces our contention that oversight from government or from publicly funded but politically neutral agencies is essential to address market failures. Effectively governing uncertain impacts of emerging technologies on the environment is critical for averting the next global environmental challenge. However, traditional approaches to developing government policy and regulation can be slow to change and often react to emerging technologies which may be too late to manage environmental impacts (as evident of incidents that have become powerful by-words, such as Bhopal, Fukushima and *Exxon Valdez*). It is inevitable that there will be other incidents, and that these will drive further debate and policy change in the future. The fact that we do not know what these will be, how serious, or what changes they will drive underlines both the importance and difficulty of issues surrounding technology, risk, and regulation. Our capacity to address global environmental challenges quickly and responsibly will, to a great extent, rely on humankind's capacity to rethink global technological governance, which, in turn, relies on developing inclusive, adaptive and innovative institutions that reflect modern dynamic circumstances.

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