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Technology and Sustainability

The term 'sustainability' has dominated the global political agenda for three decades despite, or possibly because, of its ambiguity. Together with other terms such as 'the Anthropocene', 'the Earth system', or 'planetary boundaries', it forms the conceptual apparatus for understanding the global impacts of an industrial civilization centred on the extraction of natural resources for economic growth and social well-being.[1] The idea that there is something fundamentally problematic in the ways in which human societies utilize natural resources of course predates the birth of the sustainability paradigm in the 1980s and its wide political diffusion since the 1990s. Notions such as the 'tragedy of the commons' in the collective use of shared resources, the impossibility of infinite economic growth in a resource-constrained world, or 'peak oil', the theoretical point which marks the beginning of the gradual decline of global oil extraction, have been evergreens for more than half a century.[2] So have ideas such as 'overpopulation' or 'carrying capacity', which refer to a theoretical maximum of human beings that may simultaneously inhabit the planet without pushing the pace of natural resource extraction above the pace with which those resources regenerate. And the vocabulary keeps growing. 'Green growth', 'decarbonization' and 'zero-carbon development' are recent visions of a global economic model that would ensure global ecological integrity by reducing the pressure on natural resources yet without compromising on economic growth as a guiding social principle. To the extent that it is not resource extraction but economic growth itself that jeopardizes the future of human civilization, 'degrowth' or the 'steady state economy' have been proposed as alternative visions. Alternatively, 'circularity' is an answer to the inefficient resource usage and waste within the confines of a capitalist and growth-centred economic order.[3]

It is certainly easier to pinpoint *what* is going wrong than to identify the exact reasons *why* this is the case. The trajectory of global greenhouse gas emissions

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puts us on a path towards high-impact climate change of possibly 3℃ by the end of the century, with an increasing probability of inadvertently triggering chaotic, irreversible and catastrophic planetary changes.[4] The rate at which species are presently being lost is up to a thousand times larger than the historical baseline and ecosystems are being degraded on an unprecedented scale, including tropical rainforest that plays a vital role in the global hydrological cycle, among other indispensable functions. The world's oceans face an existential crisis from overfishing, sea-surface temperature increases, higher acidity levels resulting from global carbon dioxide emissions and zero-oxygen 'dead zones' in coastal areas due to fertilizer run-offs in agriculture, as well as pollution with oil, microplastics and other harmful substances, among others. Coral reefs, a key element in marine ecosystems and a host of vast genetic diversity, will for the most part be lost by the middle of this century. All this is accompanied by significant long-term growth rates in world population, in the extraction volumes of natural resources such as minerals, fossil fuels and biomass, in urbanization, in industrial pollution and in a wide range of other indicators that work against a healthy and viable relationship between human societies and their natural environment.[5] The global material footprint of human societies, presently amounting to more than 85 billion metric tonnes of minerals, ores, fossil fuels, and biomass,[6] can manifest itself in curious ways at the local level – for instance in an increasing scarcity of sand. As sand is used in the production of diverse materials (including, notably, concrete), and as the global consumption of those materials increases, it is becoming a valuable and scarce resource. Where resources are scarce and valuable, and governance is weak, crime is just around the corner: the rise of 'sand mafias' in Jamaica, Morocco, and Indonesia drastically shows how even sand – the epitome of limitless abundance – can turn into an object of resource conflicts through a combination of ineffective governance, misaligned economic incentives and limited planning horizons.[7]

In the broadest sense, sustainability refers to the need for far-reaching social and economic changes in order to ensure that the natural resource base on which contemporary civilization is founded remains intact for the foreseeable future, and that human societies are shielded from the worst pressures associated with global environmental change. This is well understood, yet of course the devil is in the details. To what extent can economic growth be decoupled from its dependence on natural resources? How far should we rely on free markets for the timely delivery of innovations that would reduce the ecological footprint of our economic model? How quickly and radically do we need to change our economies and societies? Do we have time for a smooth and painless transition or does virtually everything have to change virtually overnight? What role do multilateral politics, particularly inside the UN system, play in guiding, pushing or prodding nation states into more responsible and forward-looking public policies in ways that ensure a minimum of global fairness? What is the appropriate balance between mitigating the causes of global environmental degradation and adapting to its consequences? Things get even muddier once we factor in ethical considerations. Does each human have the right to an equal share of the global environmental resources, and, if yes, how do we justify differences in resource consumption across countries, regions and social strata? When distributing the financial and other burdens of mitigating global environmental degradation, should the respective historical responsibilities of countries matter? If yes, how far into the past does historical responsibility extend? How should the rights of future generations be weighted in relation to the rights of present generations, and how far into the future do these rights extend?

Regardless of how we look at such questions, technology is central for securing environmental sustainability over the long term. Whether it is deep socio-economic transformations or marginal adjustments to the market-based global economic order, whether we distribute the political responsibilities for reducing anthropogenic impacts on the global environment in one way or another, or whether we prioritize adaptation and resilience over the mitigation of anthropogenic pressures (or the other way round), technology is a central element of the overall puzzle, no matter what. Some technologies need to disappear, from polluting industrial production processes and the internal combustion engine up to fossil-fuelled energy generation. Other technologies need to be developed, diffused and scaled, from renewable energies and electric vehicles up to climate-resilient crops, whether transgenic or not. Clearly, though, there are important differences between technologies such as, say, wind turbines and microbes used for cleaning up industrial spills; between industrial systems for capturing carbon dioxide from ambient air and satellite systems that monitor global deforestation; or between aquaponic food production systems and desalination plants. This means we need ways of thinking about technology in the context of environmental sustainability in a more systematic manner.

One way of doing so is through typologization in two dimensions. In the first dimension, we can broadly distinguish between *incumbent* and *novel* technologies. Incumbent technologies are firmly established and their scientific, technical, economic and other properties are generally well understood. Incumbent technologies are fully integrated into wider socio-technical systems, which encompass their 'production, diffusion and use'.[8] In contrast, novel technologies are either still undergoing research, development and innovation or they are only in the early phases of diffusion and adoption. They tend towards considerable ambiguity and plasticity, meaning that their eventual characteristics and also their ultimate social, economic and other functions are not determined in advance.[9] This also means

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that their benefits, risks, prospects, impact and relevance are usually difficult or even impossible to predict. In a bon mot attributed to the futurologist Roy Amara, '[w]e tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run'. Novel technologies may appear under the radar and turn out to be game changers, or novel technologies may appear to be game changers but turn out to be little more than hot air.

In the second dimension, we can distinguish technologies with incremental impacts from those that are *transformative* in character. This does not refer to their 'relevance' or 'importance', but rather their efficiency in terms of the ratio between their (actual or potential) impacts and the resources that are required for their deployment and operation. Consider solar power: the story that is usually told is how solar power has, in many parts of the world, reached grid parity with fossil power sources, driven by remarkable efficiency improvements in solar cells, by smart public policy support and in spite of the obscene direct and indirect subsidies that continue to be channelled into the support of fossil fuels.[10] This is all true, of course, although the flipside of this narrative is that solar power simply does not have the leverage for displacing fossil power systems in one fell swoop, while decades of subsidies and political support have so far failed to push its share in the global electricity mix above 3 per cent. While solar power is likely to gradually evolve into a central pillar of the global energy system during the course of this century, it presently amounts to little more than tinkering at the margins. In contrast, transformative technologies possess significant leverage in the sense that little effort is required for causing large impacts. In the digital sphere, for instance, machine-learning techniques can recognize latent, low-dimensional structures in messy, high-dimensional data in ways that go beyond the computational capacities of conventional algorithms. The nuclear bomb offers a destruction-to-cost ratio that is significantly higher than that of any conventional weapons. In the environmental domain, as I will discuss in this book, transformative technologies offer vast potential for the resolution of global environmental challenges that may not have conventional solutions, or that may be comparatively costly or difficult to solve otherwise. Yet, a particular twist about transformative technologies is their high degree of ambiguity: their impacts may be beneficial, they may be adverse, or we might be unable even to properly identify to what extent they are beneficial or adverse, including because observers might differ on the exact meanings of 'beneficial' and 'adverse'.

This book centres on technologies that are both 'novel' and 'transformative', and the rest of this chapter provides a broader contextualization of technology in the context of environmental sustainability. I start out with a discussion of 'transition', 'transformation', and 'resilience' as key concepts in the global politics of environmental sustainability. There are important differences between these concepts and, although I will loosely refer to sustainability *transitions* throughout this text, I use the term as a broad and somewhat fuzzy heuristic device rather than committing to it at a deeper, theoretical level. I afterwards discuss the notion of the 'techno-fix', a concept that plays a central, albeit somewhat dubious, role in the contemporary discourse over environmental sustainability and technology. I then develop the notion of technological 'promises' and 'perils' as the foundation of my theoretical framework. Afterwards, I discuss the issue of 'ambiguity' – that is, the problem that the promises and perils of a technology can be uncertain or disputed. The chapter concludes with a short discussion on whether a transition to environmental sustainability necessarily implies one or the other form of 'techno-fix'.

2.1 Transitions, Transformations, Resilience

In the broadest possible sense, there is a need for societies to cope with the global sustainability crisis, and technology, in one way or another, plays a role in this. Across all levels, we are dealing with different types of change: environmental change induced by changes in human societies, pressure on human societies to change in order to adapt to environmental change or attempts to *prevent* environmental change from unduly changing human societies (for instance, by inducing societal collapse). In other words, there is substantial conceptual confusion and ambiguity in the sustainability debate. To some extent, this is because the objectives of what we might broadly call the global politics of sustainability are unclear: is it to preserve our social models in the face of environmental change through smaller technocratic adjustments within the confines of the contemporary global economic order? Is it to change the social and economic foundations of contemporary societies so that humans may live in greater harmony with nature? Is it to halt, slow down or reverse harmful processes of global environmental change? The answer very much depends on what we mean by 'change', both at the level of the global environment and that of human societies. Transition, transformation, and resilience as central concepts in the contemporary debate on environmental sustainability differ in precisely this: the meaning they accord to the notion of 'change'.

The term *transition* is perhaps the most ambiguous of the three. In one influential definition, it is 'a fundamental transformation towards more sustainable modes of production and consumption',[11] which simply shifts the definitional burden to another concept: that of 'transformation'. The same problem can be found in other definitions of sustainability transitions as 'processes of fundamental social change in response to societal challenges',[12] or as 'large-scale disruptive changes in societal systems that emerge over a long period of decades' and 'are a threat to existing dynamically stable configurations facing persistent sustainability challenges'.[13] Sustainability transitions are backcasts from desirable futures – in that sense, they are different from other historical transitions (such as the Industrial Revolution) because they are purposive rather than emerging from decentralized and uncoordinated actions.[14] Research on sustainability transitions has become something of a cottage industry over the past two decades and today revolves around the notion that processes of change are driven by interlocking factors that operate at different scales.[15] As transitions necessarily involve distributional conflict between various interest groups, a significant amount of research has dealt with the political barriers to sustainability transitions and the question of how to overcome them.[16] While transitions can take place in various ways and at various scales,[17] the paradigm itself is geared around gradual adjustments to market economies through a combination of innovation and public policy incentives. The notion of transition is thus strongly aligned with concepts such as the green economy, or the circular economy, that revolve around the supposed complementarity between environmental sustainability and the capitalist socio-economic order, giving ample room for win–win situations as profitable new business opportunities arise in clean energy and other fields.[18]

The term *transformation*, in contrast, resonates with diverse perspectives rooted in ecological Marxism and heterodox economics. A common thread is to directly link the global environmental crisis to the capitalist mode of production. One influential concept derived from Marxian thought is the notion that capitalism produces a 'metabolic rift' in the interactions between human societies and nature.[19] Others have substituted the notion of the Anthropocene with that of the 'Capitalocene' as a specific way of organizing nature.[20] Another common thread is the idea that nature imposes hard limits on economic development, as finite resources do not allow for infinite growth. This idea was popularized by the Club of Rome's 1972 report on *Limits to Growth*[21] and has been a matter of fierce debate among economists ever since. What is at stake in this is the question of whether economic growth, particularly in the context of a capitalist economic order organized around the appropriation of surplus value, is part of the solution for the global environmental crisis or part of the problem. For diverse critical and heterodox thinkers, it is decisively part of the problem. One conclusion is that environmental sustainability may require the purposive *reduction* of the global economic footprint, or *degrowth*.[22] This means abandoning central features of the market economy, including interest, banks and the financial sector, and more generally pulling the rug out from under the entire contemporary social and economic order.[23]

Resilience, finally, offers yet another perspective on the problem of environmental sustainability. This perspective addresses the stability of socio-ecological systems. Resilience can refer either to the capacity of socio-ecological systems to bounce back to their equilibrium state in response to disequilibration or to their capacity to 'absorb disturbance and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks'.[24] These are two quite different ways of understanding the concept, and the literature on resilience is, in general, characterized by significant conceptual ambiguities. At the most abstract level, though, resilience is about the means and conditions for socio-ecological systems to stay the same: either by bouncing back to an attractor point in response to perturbations or via internal adjustments that allow them to cope with pressure without jeopardizing their essential characteristics. This second perspective accordingly comes close to the central tenets of transition theory,[25] the defining difference possibly being 'that resilience scholars have focused mainly on the capacity of socio-ecological systems to deal with disruptive change, whereas transition management scholars have focused on achieving non-linear change in socio-technological systems'.[26]

Transitions, transformations and resilience are thus very different ways of looking at the problem of environmental sustainability and they involve quite different understandings of what should change and what should not. How far these differences matter in practice is not necessarily clear, though. A 'safe' global warming target of 1.5℃ by the end of the century requires 'rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems' that are 'unprecedented in terms of scale', according to the Intergovernmental Panel on Climate Change.[27] According to the International Energy Agency, a 1.5℃ pathway requires 'nothing less than a complete transformation of how we produce, transport and consume energy'.[28] This undoubtedly classifies as a transition and could just as well be understood, from a resilience perspective, as adjustments to system parameters without changing fundamental system characteristics. And although such processes may not be *intended* as a transformation at the level of the wider social and economic order, it could well entail changes in the structure and distribution of political and economic power that may help bring such a transformation about.[29] Regardless of exactly how we think about it, technology is central: for blunting the edges of industrial civilization, for facilitating more dramatic and far-reaching changes in social and economic organization, but also in terms of the powerful social, environmental, and political risks it can create.

2.2 Techno-Fixing Sustainability

The role of technology in environmental sustainability is contested, and that is putting it mildly. On one side of the spectrum, there is blind trust in the power of technological innovation to deliver us from the evils of global environmental degradation. On the other side, technology and its control by unaccountable mega-corporations and billionaire philanthropists with dubious political agendas is itself a central element of everything that is going wrong in this world. Towards the middle are proponents of controlled use based on case-by-case decision-making, subject to rules that ensure proper monitoring, risk assessment, transparency, public participation, social equity, and compensation for inadvertent harm, among other issues. Such differences in perspective are not trivial. Political disputes over ends pose much more demanding governance challenges than disputes over the means for achieving ends that are collectively accepted. Differences in the perception of the distribution of costs, benefits, and risks associated with different technologies are a significant impediment to the creation of effective governance structures. This problem tends to be exacerbated for novel technologies, as the large associated scientific uncertainties increase the amplitude of disagreement and as strong asymmetricity in the distribution of technological capacities between originator states and others implies strong polarization of regulatory preferences.

The specific role of technology with regard to the sustainability challenge is thus a matter of sharp contestation. For some, technology promises solutions to the challenge, by reducing the dependency of the global economy on natural resource inputs, by mitigating the social and environmental impacts of unsustainable resource consumption or by supporting societies in adapting to such impacts. Whereas the Panglossian view is that such technological solutions are best delivered through unfettered free-market innovation, the more cautious perspective is that effective governance is required for unlocking the potential benefits of technology for sustainability. For others, technology is a part of the problem rather than the solution. Coping with the sustainability challenge accordingly means banning, or at least strictly controlling, new technologies that may directly or indirectly increase the ecological footprint or assorted social vulnerabilities. In this camp, the more moderate view is that effective governance can limit the negative social and environmental implications of technology while allowing for the capture of its benefits.

The debate thus revolves around two issues. The first is technology *and* governance: how should technology be governed, and for what ends? The second is technology *or* governance: how far does governance (or, rather, the stifling effects of over-regulation) prevent technological solutions from being unlocked, or how far does technology create problems by crowding out alternative political solutions? It is this second aspect which, nowadays, revolves around a term that is mostly used in a derogatory manner: the 'techno-fix'. This term refers to the supposed tendency in high-tech societies to find convenient technological solutions for problems that are political in nature and would, accordingly, require political rather than technological solutions. This modern use of the term 'techno-fix' is thus rather similar to the term 'solutionism', a technocratic ideology ascribed to Silicon

Valley entrepreneurs with their alleged belief in elegant and simple innovation-based solutions for complex societal challenges.[30] Yet, the origins of the term are more complex and date back to debates on social engineering in the context of Lyndon Johnson's Great Society programme of the 1960s: while the Johnson administration sought to fix key ailments plaguing US society in areas from education and health care up to civil rights, broad-based technological innovation, from computers and transportation up to industrial mass production, led to the question that, '[i]n view of the simplicity of technological engineering, and the complexity of social engineering, to what extent can social problems be circumvented by reducing them to technological problems?'.[31]

The concept of the techno-fix thus opens up a two-part question: to what extent *can*, and to what extent *should*, complex social and political issues be addressed through attempts at devising simple technological solutions? It is important to keep these questions separate: it is one thing to claim, perhaps correctly, that technological solutions are simply ineffective for some of the most pressing challenges confronting the contemporary world, including in the domain of environmental sustainability. Yet it is something else entirely to ask how such technological reductionism compares to the alternatives, meaning the conventional and somewhat pedestrian solutions within the domain of standard public policy. It is not *just* that any given techno-fix offers an easy solution, whether rightly or wrongly; the techno-fix must always be evaluated in comparison to its alternatives. It is, in that sense, always a second-best solution which, most of the time, we would not even be considering were it not for the common (and possibly systemic) failures of standard public policy, including at the international level.

The concept of the techno-fix is thus slightly more complex than its typically polemical usage might suggest. There are two additional aspects worth considering. The first is that there is a thin line between the consideration of imperfect technological solutions for problems that would otherwise be largely intractable, and technological hubris. This hubris manifests itself as overconfidence in the capacity of humans to control and command the environment and the resources which it contains via technological means.[32] Particularly egregious examples include nuclear power that is not only safe but also 'too cheap to measure'; the agricultural biotechnology industry that, despite being in business for more than three decades, continues to promote itself on little more than vague promises of revolutionary future breakthroughs; or 'clean coal', the somewhat recent idea of combining coal power with technology for the capture and storage of carbon dioxide and other pollutants emitted during combustion, supported by virtually nobody outside of the coal industry. For none of these examples do we have robust evidence that they fix anything of substance except corporate bottom lines. Yet it is too easy to dismiss these and other cases as mere instances of corporate public relations. To some extent, there is likely a genuine belief within the respective corporate and scientific milieus that nuclear power can be made both safe *and* cheap, that agricultural biotechnology will deliver tangible solutions for food safety and the climate-resilient development of food systems, or that coal power can be combined with carbon capture and storage at competitive levelized costs. While the overselling of technological solutions is ‘business as usual’, the ideological foundations that give rise to genuine technological hubris arguably constitute a much greater challenge when trying to come to terms with the role of technology in the context of environmental sustainability.

The second aspect that should be considered is the propensity for polemics in contemporary debates on various types of techno-fixes. It is possibly true that techno-fixes can amount to inappropriate solutions for problems that would better be addressed through conventional and burdensome political processes with limited effectiveness. At the same time, though, there are few (if any) proponents of blindly throwing dubious technological solutions at complex problems of environmental sustainability without any accompanying governance components. Particularly in fields like biotechnology and climate engineering, there is a good deal of hyperbole among activists and civil society organizations that decry techno-fixes as derelictions of political responsibilities, typically on behalf of corporate interests. While this way of looking at it cannot always be dismissed out of hand entirely, it trivializes the complex governance debates that, for any kind of technology, are always part of the wider landscape. Another problem with common uses of the term is that its scope is not properly defined. Is everything that involves technology, no matter how and no matter its type, a techno-fix? If climate engineering is a techno-fix for climate change, does this make wind power or hydrogen fuel cells into techno-fixes as well? Why should we consider only one of those as an inappropriate and ineffectual technological solution for a political problem? If transgenic seeds are a techno-fix for problems of the global food system, what about hybrid plants or mutation breeding, techniques that have been permanent fixtures of agriculture for almost a century? In other words, where do we draw the line and why?

The concept of the techno-fix, while certainly problematic, draws our attention to important aspects in the politics of environmental sustainability: a potential over-reliance on technology and potential overconfidence in our ability to harness and control it, the need to properly integrate technological solutions with political solutions, and the possible intractability of diverse challenges in the broader problem field of environmental sustainability and the associated widespread failure of conventional solution approaches. At the same time, the concept of the techno-fix is misleading in one crucial way because, in the absence of adequate governance arrangements, technology does not fix anything. The reverse image to the unjustified belief in the problem-solving capacity of technology, in any case, may well be the *regulatory fix*, meaning overconfidence in the problem-solving capacity of political institutions despite substantial evidence for their limitations.

2.3 Technological Lock-In

Perhaps a deeper reason for the ambiguities that bedevil the concept of the techno-fix is the implicit background assumption that 'technology' amounts to simple material artefacts. But this is only part of the story. Technology is always bound up with wider social structures. Just as for institutions, technology can become sticky. In fact, many contemporary problems related to environmental sustainability derive from the stickiness of technologies that are generally understood as undesirable. Imagine if technologies were adopted in purely instrumentalist fashion, based on cost–benefit analyses entailing environmental full cost accounting: coal power would long be out of the door by now and the world would draw most of its electricity supply from wind and solar, plastic pollution would not exist because industry would have adopted biodegradable alternatives, biodiversity would not be at risk from the excessive use of toxic biocides, ships would be designed with a view to the elimination of noise pollution and operational vessel-source discharges, and the internal combustion engine would have been replaced with clean alternatives a long time ago.

The reason why these things are not happening despite their obvious advantages is due to lock-in: technologies and the social structures in which they are embedded tend to be self-reinforcing, meaning that, as time passes, they become increasingly difficult to change even when alternatives exist that are clearly superior. If the world would rationally design a global energy system from scratch at this point in human history, it would look completely different to the fossil fuel-based system that has emerged and consolidated itself since the mid-nineteenth century. The same goes for global agriculture, transportation, public health, and practically any other sector related to sustainable development. The literature discusses many drivers of self-reinforcement that may lead to technological lock-in. Learning effects can gradually increase the utility that societies can draw from a given technology, thus reducing the relative attractiveness of switching to technological alternatives. Special interest groups may be able to extract rents from unsustainable (or otherwise undesirable) technologies, enhancing their capacity to capture regulatory processes and to increasingly entrench themselves in the political economy.[33] Thus, even where sustainable alternatives are desirable from a perspective of collective welfare, status quo biases in techno-institutional complexes may cause unsustainable patterns of production and consumption to continue unabatedly.[34] In a very basic sense, then, markets do not select technologies based on the comprehensive analysis of social costs and benefits, meaning that collectively undesirable technologies may persist despite the availability of feasible alternatives.

There is broad discussion on the factors that allow (unsustainable) technological lock-in to be overcome. In transitions research, major importance is assigned to game-changing technologies that first develop in sheltered niches, where, for instance, they may be shielded from competitive pressure, and subsequently emerge to disrupt and transform wider socio-technical systems.[35] A prime instance of this is solar power, in many countries and regions supported by dedicated policy instruments and excluded from direct competition with incumbent fossil power generation until reaching grid parity. More generally, novel technologies may help to overcome unsustainable technological lock-in – but it may also mitigate its impacts without changing anything about the problem of lock-in itself! Carbon capture and storage, for instance, is a technology that squarely falls into this latter category, mitigating the effects of locked-in fossil power generation without making any direct contribution to shifting energy infrastructure towards renewable alternatives. Phenomena such as this would perhaps allow for a better use of the term 'techno-fix', as technological band-aid solutions intended to offset negative impacts caused by *other* technologies and thus sustaining their lock-in. Finally, for the purposes of environmental sustainability, there is another major aspect to this: besides *facilitating* unsustainable technological lock-in, the emergence of novel technologies may also generate new forms of lock-in.[36] This may have long-term consequences which are difficult to predict but not necessarily beneficial from the perspective of environmental sustainability – including because of the crowding out of potential alternatives, as I will discuss further.

Accordingly, there are crucial aspects related to the temporality of technology and technological change that I deal with in only a cursory manner here. For now, suffice it to say that a long-term perspective on environmental sustainability suggests two things. On the one hand, novel technologies are, in one way or another, crucial elements of larger solution packages for the various challenges of environmental sustainability. On the other hand, there is a need for caution regarding the potential role of novel technologies in the stabilization of unsustainable lock-ins and, especially, regarding the shift towards novel types of lock-in that are *motivated* by concerns over environmental sustainability yet may cause various unintended and undesirable effects over longer time horizons.

2.4 Promises and Perils

In an attempt to think about technologies in the context of environmental sustainability in a systematic manner, at the core of my conceptual framework is the analytical distinction between technological 'promises' and 'perils'. These define the purpose of governance: making 'good' things happen and preventing 'bad' things from happening. What is 'good' for one actor is not necessarily so for others, though, meaning that beneficial and detrimental effects can be distributed in quite uneven ways. TNTs hold a particularly large potential for causing both 'good' and 'bad' things. For the time being, this remains a potential – and one that is to a certain extent untested. I adopt the language of promises and perils to designate exactly this latent capacity and to highlight that the degree to which promises will be realized and perils avoided in the future depends to a large extent on institutional responses and other governance choices in the present.

I understand the promises and perils which TNTs imply for environmental sustainability in a broad and abstract sense, for one because their relevance extends far beyond what could be expressed in, for instance, the quantitative terms that enter into cost–benefit analysis. Another reason is that these technologies are moving targets in the sense that they are still in a process of emergence and neither their definite technical characteristics nor the ways in which they will end up being embedded in wider social contexts can be predicted with confidence.[37] This amorphous quality, where technology, politics, and regulation are evolving together in unpredictable ways, is also meant to be captured by the terms 'promises' and 'perils'. One important caveat is that, while the conceptualization that follows arguably offers a useful way for thinking about the 'positive' and 'negative' aspects of TNTs at an abstract level, it is not necessarily exhaustive. It does, however, cover several elements that are at the centre of the contemporary political and academic debate on environmental sustainability: harm and harm mitigation, fairness and equity, public goods and the commons, as well as problems sometimes (incorrectly) referred to as moral hazard. While unlikely to be exhaustive, this conceptualization offers a useful entry point for thinking about the 'positive' and 'negative' sides of TNTs but also about technology more broadly, an issue to which I return in Chapter 7. Importantly, technological promises and perils are here understood specifically with regard to environmental sustainability, at the level of the global environment as well as society–nature relations, and not regarding human well-being, aggregate social welfare, or other, more abstract referents.

The promises of TNTs entail *impact management*, *knowledge and information commons*, as well as the *mitigation of global injustice*. The first of these captures technological capacities for managing anthropogenic impacts on the environment and environmental impacts on societies. Technology can mitigate anthropogenic impacts on the global environment by reducing natural resource consumption and by reducing or reversing harmful externalities on natural resources from human activities. Impact management thus addresses the extraction of natural resources at unsustainable levels but also unintended harm to natural resources as a result of other, often unrelated, social and economic actions. Impact management as

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a systemic socio-economic feature is at the core of various contemporary master discourses, or imaginaries, on sustainable futures. One of these is the bioeconomy: an imagined future economy that primarily relies on renewable resource inputs from biomass. In the power sector, renewable biomass, including from waste, converts into electricity with low or net-zero carbon dioxide emissions. In combination with technologies for capturing and storing the carbon dioxide that is emitted during biomass combustion, emissions from power production even become negative: energy crops bind carbon in their cell mass during growth, preventing this carbon from being re-released, which reduces the overall atmospheric greenhouse gas stocks. In transportation, next-generation biofuels contribute to decarbonization and the reduction of harmful air pollution, but without causing harmful effects on biodiversity and the land system in the way that current biofuels frequently do. Bio-based materials offer viable substitutes for plastic, reducing marine pollution as well as oil consumption in the petro-chemicals industry. A similar concept, the 'blue economy', would see greater sustainability through the use of marine resources. Anthropogenic pressure on fish stocks could be reduced by scaling up aquaculture – that is, industrial fish production in semi-contained settings.[38] Aquaculture presently faces various challenges that are far from appealing to customers, such as the rapid spread of infectious diseases. Pharmaceutical interventions and genetic modifications would, in principle, offer ways of minimizing disease outbreaks, thus improving the economics of aquaculture and, accordingly, reducing anthropogenic pressure on fish stocks in the oceans. The same applies to genetic modifications for improving yields in agriculture. Already, we are seeing how transgenes that control the production of growth hormones are improving economic productivity in agriculture. While customers might find such technical details of aquaculture revolting, the fact that this might constitute a highly effective way of reducing anthropogenic pressure on the oceans also highlights the ethical complexities at the sustainability–technology interface.

The 'bioeconomy', the 'blue economy', and related concepts such as the 'circular economy' elevate the management of anthropogenic impacts on the global environment to the systemic level. Yet not all anthropogenic impacts on the environment will be avoidable, and many of those will feed back on human societies, where they will cause various types of harm. Some adverse environmental impacts on human societies result from natural factors that are themselves only marginally affected by human activities. Others occur naturally yet increase in frequency or severity due to anthropogenic factors. Social vulnerabilities to these environmental changes are strongly variegated. Least-developed countries cannot compensate residents for loss and damage from natural disasters. Small island states face existential risks from sea-level rise, some littoral states confront significant threats from flooding, and landlocked states do neither. Societies with sophisticated food supply chains do not depend on wildlife hunting for their livelihoods. Large exporters of natural resources are vulnerable to sudden decreases in commodity prices whereas larger importers are vulnerable to sudden increases. To be sure, many harmful environmental impacts on human societies reverberate beyond national borders. Biological invasions can devastate the economies of agricultural net exporters but also cause indirect harm through the disruption of global food supply chains. TNTs, just as technology more generally, can help to reduce, avoid, or reverse such impacts. Some may even go in both ways: facilitating the management of human impacts on the environment while also helping to control environmental impacts on human societies. For instance, as I discuss in Chapter 4, bioinformatics can improve the food security of human societies in the face of declining agricultural biodiversity while simultaneously offsetting some of the harmful environmental impacts of contemporary industrialized agriculture.

A second promise which TNTs can entail is the production of *knowledge and information commons*. This means it can enable or facilitate the creation and unrestricted accessibility and usability of knowledge and information with positive (direct and indirect) environmental spin-off effects. For one, by unlocking new ways of exploring and studying nature, technology makes crucial contributions to scientific progress, thus improving our understanding of the environment, with all its intricate and complex causality, thereby creating better possibilities for anticipating, managing, and responding to global environmental changes. Satellite images and other types of remote sensing have been absolutely indispensable for studying everything from global vegetation patterns to ocean currents to cloud formation. Contemporary climate science would not exist without computer simulations used in integrated assessment models and similar applications. New radiological techniques enabled the structure of DNA to be discovered in the early 1950s, which lay the groundwork for modern evolutionary biology and ecology. This and other advances in human knowledge not only lead to increases in the effectiveness of environmental policies, they also allow hitherto unknown problems with potentially catastrophic impacts to be identified in advance. Without NASA's ozone mapping spectrometer making it possible to gauge the full extent of ozone depletion during the 1980s, it is quite unlikely that governments would have phased out emissions of chlorofluorocarbons and, in doing so, prevented global UV irradiance from reaching dangerous levels.[39] The same, of course, goes for climate change and techniques that allowed the reconstruction of the geological temperature record. Of course, technology-driven scientific progress also contributes to innovations with more direct and tangible sustainability benefits. These operate not at the level of knowledge, but also of information. Such information may, for instance, facilitate the enforcement of environmental regulations. Modern spectrometry not only allowed the initial detection of ozone depletion but also, decades later, the detection of non-compliance with international rules on ozone-depleting gases.[40] For sure, the benefits that result from such technological advances can be realized outside of a commons regime, where knowledge and information are accessible and usable without restriction. Technology can also enable or facilitate the creation and supply of information and knowledge with beneficial spin-off effects for environmental sustainability under other regimes, notably proprietary ones. However, the public good characteristics of knowledge and information, where their consumption by one actor does not reduce their availability for other actors, implies that a commons regime maximizes the benefits that societies, collectively and in aggregate, can draw from technologies. Knowledge and information commons, in addition, correct for global asymmetries that result from geographically uneven socio-economic development and the exclusionary appropriation of technological benefits by innovator economies.

This brings us to the third and final promise of TNTs, the *mitigation of global injustice*. The concept of justice, including in a global context, is of course of daunting complexity and I will steer clear of its many nuances and subtleties.[41] I understand (in-)justice in its distributional dimension – that is, in relation to the allocation of 'goods' and 'bads'. For the purposes of environmental sustainability, such distributional injustice would relate to the geographical incongruence between societies that are the primary originators of harmful environmental changes and societies where the associated impacts overwhelmingly accumulate, or to the incongruence between the custodians of natural resources and the profiteers of their commercial and other utilization. We can conceive of such injustice both over larger historical timescales or at the level of isolated time slices. Technology, including TNTs, can provide a tool for rectifying global injustice, by directly intervening with asymmetrical patterns of costs and benefits, as well as, indirectly, by contributing to the effectiveness of governance arrangements designed for remediation.

Understood along these lines, TNTs hold significant potential for getting the global environmental crisis under control in a fair and effective manner. At the same time, all of the technologies that will be discussed in greater depth later in this book have significant downsides and some of them carry potentially enormous risks. This should not be trivialized, although the reason why these technologies are a matter of discussion in the first place is, of course, that conventional approaches for getting to grips with the challenges of global environmental sustainability have not met with a great deal of success thus far. Moreover, the political context that has produced these challenges is characterized by strong inertia and is thus inconducive to the transformative changes that, in principle, would be required. The leverage granted by TNTs might (!) thus provide a workaround solution, and the extent to which we are able to realize their associated promises and to avoid their associated perils ultimately hinges on the suitability of governance arrangements, including at the level of international institutional responses.

With that in mind, I propose three broad sets of perils: *environmental harm*, *crowding out of feasible alternatives*, and *aggravation of global injustice*. The potential to cause significant environmental harm is likely the most straightforward reason for being sceptical of technological approaches: rather than safeguarding environmental sustainability, technologies might end up causing harm. Issues of environmental harm tend to be complex. In one way or another, *all* technologies cause *some* kind of harm. In many cases, this harm might either be marginal in itself or negligible in contrast to the overwhelming benefits that a technology simultaneously produces. Usually, we would thus refer to *net effects*: the benefits produced by a technology minus its costs. While this sounds good in theory, it can pose problems in practice. Wind farms are an essential component of the clean energy transition yet can cause non-trivial harm to bird populations when constructed in migration corridors. Do the benefits of clean energy outweigh the harm done to the birds caught in the turbines? Probably – although it is not necessarily clear to what extent this conclusion would follow from a rational analysis of costs and benefits and to what extent from normative predispositions that, in any case, tend to be biased towards human rather than non-human life. Or consider the recurring debates on nuclear power and climate change, which are generally pretty far from anything resembling reasonable disagreement among informed interlocutors. While nuclear power is a low-carbon energy source and thus in principle beneficial for the mitigation of greenhouse gas emissions, its scale-up would also intensify risks associated with reactor safety, proliferation, and the management of spent nuclear fuel. Estimating the environmental net effects from a potential scale-up of nuclear power is thus far from trivial due to the incommensurability of these different dimensions, but also due to profound disagreement on the economic feasibility of nuclear power or on the extent to which it might provide a remedy for the intermittency of power supply in large-scale renewable energy systems.[42]

People on both sides of the argument would likely agree that both wind farms and nuclear reactors produce certain harms as well as benefits, yet the weights which we respectively assign to different types of harms and benefits do, to a certain extent, depend on our normative outlook. We might argue that, since climate change subjects bird populations to various types of harm, the aggregate benefits to birds (of avoided climate change through wind energy) outweigh aggregate harm (of being caught in the turbines). We might also argue that the economics of nuclear power are abysmal when compared to renewable energies; that the supposed contribution which nuclear energy would make to solving the intermittency problem of renewables is vastly exaggerated; and that no complex technological system, including nuclear reactors, can ever be fully proofed against catastrophic failure.[43]

But other things come into play as well, such as temporal discounting (e.g. how do we weigh present gains from low-carbon, nuclear energy relative to the future costs of final storage?), spatial discounting (how do we value our respective local environments relative to environments elsewhere on the planet), or risk tolerance (do we prefer small gains or losses occurring with high probabilities over large gains or losses occurring with low probabilities?).

What exactly counts as 'harm', and how exactly we would estimate the net effects of a harmful technology, is thus a problem with a tendency towards intractability. As Chapters 4–6 will show, this problem is often at the core of political disputes at the technology–sustainability interface. Regardless of how we conceptualize and measure harm, though, it is probably safe to say that there are certain types of harm that would generally be considered excessive relative to the benefits which a given technology is supposed to deliver. For instance, it is difficult to imagine a scenario in which societies would accept catastrophic damage to the ozone layer as a side effect of a global programme for stopping climate change through stratospheric aerosol injections (although this would immediately beg the question of how to define the threshold criterion of 'catastrophic').

A second technological peril is often incorrectly referred to as 'moral hazard' and will here be designated as the *crowding out of feasible alternatives*.[44] This peril results from the irreversibility of many social choices. Societies may choose to invest in renewable energies at a level consistent with international climate targets or they may choose to underinvest in the expectation of later offsetting the differential via technologies for the removal of atmospheric carbon dioxide. What they *cannot* do, however, is to see how either version plays out and, in the case of being dissatisfied, travel back in time in order to try out the alternative choice. The same goes for agriculture. Societies may choose to invest substantial resources for transitioning away from a system of intensive agriculture that overuses fertilizer and pesticides for a small number of cash crops with limited genetic diversity, that relies on heavy-handed pharmaceutical solutions for countering the health threats that are a by-product of the mass production of animal protein, and that gives outsized economic and political clout to the cartels that dominate the international markets for seeds, agrochemicals, livestock, and farm equipment.[45] Or they may choose not to. Yet if they do not, they may end up in a situation in which there are no longer any feasible alternatives to risky genetic interventions for coping with the evolved resistances, with potentially devastating consequences for crops, livestock, and thus also food security more broadly. The crowding-out problem, in other words, means that technology might end up not delivering on its promises and, by the time this turns out to be the case, it is too late to reverse course.[46] That is, the false future promises of technology can detract from less attractive albeit workable solutions that are available in the present yet will increasingly slip out of reach as time goes by.

The third technological peril, the aggravation of global injustice, is about the distribution of technological benefits, costs, and risks: who is entitled to which share of benefits, who has to shoulder what kind of costs, and who must face which risks? As with the corresponding technological promise discussed earlier, this peril is based on a distributional concept of justice. Without putting too fine a point on it, novel technologies can impose costs and risks on societies that have particularly pronounced vulnerabilities or specific developmental needs. Low-carbon transitions, for instance, are typically framed as win–win situations that combine environmental sustainability with economic growth and human development, yet may also create ‘a fulcrum for elitism, discrimination and the consolidation of wealth’.[47] Technology can also deprive societies of benefits that they have a legitimate claim to. Modern biotechnology, for instance, can deprive them of commercial and other benefits that derive from plant genetic resources which they have stewarded for centuries.[48] What complicates the consideration of such distributional effects is that they can be highly uncertain. Technological risks may only gradually become obvious over time and remain contested even then. What counts as benefits may also be unclear: proprietary rights over new technologies, or over natural resources appropriated via new technologies, are typically justified in terms of their public benefits. Without such rights, so the argument goes, societies would receive fewer welfare-enhancing goods and services. Yet the extent to which private profit-seeking, as such, amounts to improvements in public welfare is an extremely complex issue on which a number of differing perspectives can be found in the history of ideas. Where distributional effects occur, they may lead to follow-up problems, such as the erosion of legitimacy or societal support for a technology, loss of the social licence to operate, or even active opposition. With matters of justice intrinsically connected to the concept of sustainability as such, distributional effects and their management are of central importance.

Overall, the ways that promises and perils are understood can differ between issue areas. The promises and perils that characterize TNTs in the environmental domain will differ from those we find in, say, artificial intelligence. Equally, it is also important to note that promises and perils can change over time *within* a given issue area. In the field of mineral extraction that I address in Chapter 6, for instance, some institutions have seen changes over time in how the promises associated with the potential large-scale extraction of critical metals are being understood, with a definite linkage to environmental sustainability only emerging during the 1990s and beyond. That is to say, promises (as well as perils) need not be conceived from an environmental perspective only, but can certainly also include more base motives related to economic growth, resource security, or other factors.

2.5 Ambiguity

For some technologies, the extent to which they present (some) of the aforementioned promises and perils is rather straightforward. We know wind power reduces the carbon footprint of our energy systems while causing limited harm to some migratory bird species or, in the case of offshore wind power, marine ecosystems. Similarly, there is no real dispute that organochlorine pesticides cause substantial environmental harm while offering only modest benefits for proofing agricultural systems against plant pests. Wind power is a key technology for the transition to environmental sustainability because, for most stakeholders at least, its harmful biodiversity impacts are negligible when compared to its contribution to global greenhouse gas control. In such cases, we do not just know what the respective promises and perils of a given technology are, we also have some sort of idea of the proportion in which these promises and perils stand to each other.

For other technologies, however, the extent to which different promises and perils are present is difficult or impossible to estimate. It is thus hard to say whether these technologies tend to be more of a problem than a solution, or more of a solution than a problem.[49] These technologies are *ambiguous*: they may have some beneficial sides, they may have some problematic or even dangerous sides, yet we either do not know or cannot agree to what exact extent this is the case. Ambiguous technologies tend to be contested: some stakeholders will emphasize the potential damage which they might cause to the global environment (accordingly preferring stringent regulation or even moratoria), whereas others will point to their potential benefits (thus preferring facilitating forms of regulation). With disagreement on the very purpose of regulation rather than merely its operational details, effective cooperation is difficult to achieve.

Transgenic food is a prominent example of this problem. For decades, proponents have stressed the environmental and health-related benefits of transgenic maize, rice, cotton, soybeans, and other staple crops. *Cry* genes from *Bacillus thuringiensis* code for natural insecticides and thus reduce harmful chemical pesticide loads. Crops such as Golden Rice can compensate for the different nutritional deficits that can be endemic to least-developed countries. In the context of climate change, crops that have been genetically engineered to withstand higher temperatures or to better resist water stress are touted as essential elements for resilient agricultural systems. Conversely, detractors highlight the risk of lateral gene transfer, or genetic pollution, whereby genetic elements unintentionally flow from modified organisms into non-modified ones, the loss of agricultural biodiversity from the large-scale cultivation of genetically uniform crops, potentially unpredictable risks to the environment or human health, or the absence of tangible benefits of transgenic over cisgenic crops. Here and elsewhere, public controversies entail complex mixtures of established facts, disputed facts, differing ways of interpreting established or disputed facts, divergent underpinning norms and values, as well as more base motives of a political or economic nature. Commercial operators will naturally tend to emphasize the benign and beneficial aspects of the technologies which they deploy, whereas civil society organizations may tend to accentuate technological risks in order to build their brand identity and to gain relevance and clout. The self-serving nature of such technology assessments does not necessarily make them wrong. Establishing a factual record about the precise impacts that any given technology has on the environment and on human affairs is one thing; reaching agreement on a factual record where norms, values, and interest diverge is another thing entirely.

Technological ambiguity thus results from a blend of scientific uncertainty and normative divergence. Science matters for technology governance insofar as it allows an approximation of risks, costs, benefits, feasibility, scalability, and other factors that figure in the calculus of decision-makers. Where some of these dimensions are unknown, the costs and benefits of different decision alternatives cannot readily be calculated and compared. This is an issue which goes beyond mere *risk* governance: the concept of risk implies that the probability and consequences of a hypothetical event are, in principle, open to quantification. Yet there are cases where neither the probabilities of an event nor its aggregate impacts, nor possibly not even its fundamental plausibility, can be readily assessed. Such Knightian uncertainty creates challenges that are quite distinct from mere technological risks.[50] To complicate matters further, such uncertainty gets easily tied up with disputes that are essentially about values; as in the example of transgenic crops, uncertainty allows stakeholders to proffer those interpretations which are most convenient to themselves by either presenting partial, incomplete, or flimsy scientific evidence as conclusive, or by stressing the need to wait for conclusive evidence and in the meantime sitting things out. For instance, in opposing giving political recognition to a major 2018 report of the Intergovernmental Panel on Climate Change, Saudi Arabia was right to point to uncertainties and knowledge gaps in climate science – yet did so in a way that conveniently aligned with the country's vested interest in sustained fossil fuel exports (while downplaying the extent to which uncertainty and knowledge gaps are constitutive components of science as such).[51] Uncertainty is thus not just about a lack of information: it is about a lack of scientific authority which might constrain and delegitimize blatant self-dealing. This is why uncertainty is just one side of the coin, and value disputes are the other. And this is also why the frequent recommendation to strengthen scientific and technological advice for ensuring better policy-making is partially misguided: better advice may reduce uncertainties, but it cannot eliminate normative divergences and incompatible interests between stakeholders, because, no matter how good the science, actors that wish to dispute its findings, its implications, or both will always find some uncertainty, no matter how small or irrelevant, to serve as a justification.

TNTs are particularly prone to the problem of ambiguity. The outsize impacts which these technologies can cause, in both good and bad ways, are extraordinarily difficult to estimate precisely. The highly ambiguous nature of these technologies also reflects the stakes that are involved: if solar modules work with lower efficiency than originally assumed, the consequences are possibly costly but definitely manageable. Conversely, if space-based mining operations accidentally lead to large releases of orbital debris,[52] the ensuing damage to satellite infrastructures could cause devastating disruptions in global telecommunications. The vast leverage that TNTs possess for causing beneficial and harmful impacts makes them into wildcards: difficult or impossible to classify as either solutions or problems and thus particularly prone to contestation and controversy. Again, 'more science' is at best a partial solution to this problem. Much more than for other categories of technology, TNTs are predestined to be projection surfaces for conflicting norms and values, adding to the complexities of their international regulation.

2.6 Techno-Fixes and Political Alternatives

To sum up the discussion so far, the rapidly progressing global environmental crisis requires urgent and comprehensive responses, yet the role which different types of technologies are supposed to play as part of the wider response portfolio is contested. I have pointed out concerns with the concept of 'techno-fix', frequently applied in an inconsistent manner and with derogatory intent. Yet I have also pointed out that there is *something* to the idea of abridging cumbersome political processes that more often than not end up leading nowhere, of finding elegant technological solutions where we wait for political solutions in vain. Naturally, such arguments run the risk of reifying 'technology' and 'politics' as disparate domains subject to either/or choices. It is certainly not the case that any sort of techno-fix would ever be implemented in a regulatory vacuum – just as it is not the case that any thinkable conventional, political approach to the sustainability challenge could ever be fully disconnected from technological issues. The techno-fix, in that sense, is a solution approach that *predominantly* relies on technology. Conversely, we may refer to approaches that predominantly rely on regulation and only accord technology a secondary role as *regulatory* fixes, in a distinction that is of course somewhat artificial. But then, given the state of the global environment, what are the prospects of the techno-fix versus the regulatory fix? What should we commit to? Are there sufficient grounds to believe in the capacity of political institutions to turn things around and secure a sustainable future for humanity in a fair and effective manner? Or can we safely rely on the ingenuity of technological solutions, with political institutions playing more limited roles in terms of contributing to the realization of technological promises and the avoidance of technological perils?

There are many good reasons to be profoundly sceptical about the role that many types of technology play in the domain of environmental sustainability. This is especially true for TNTs, with their inherent risks and associated Knightian uncertainty, their scale and irreversibility, as well as the ways in which they might reinforce unsustainable social power structures. Novel biotechnological methods could serve to save industrialized agriculture from the negative environmental impacts which it produces, rather than contributing to a transition, or transformation, towards agricultural systems that are sustainable in the sense of not requiring extensive error correction through technological interventions. Technologies for climate engineering can buy humanity more time for bringing anthropogenic greenhouse gas emissions down to net zero, which is another way of saying that it extends the life span of unsustainable consumption and production in sectors from energy to transport to carbon-intensive heavy industries. The mining of critical technology metals, in the deep seas, in Antarctica, or even in space, may well add fuel to the fire of a global economic model based on unbridled growth, extractivism, and externalization of environmental harm.

To be perfectly clear: if the question is whether we should use high-risk genetic engineering technologies on wild populations, whether we should mask global warming by injecting aerosols into the stratosphere, or whether we should drill in vulnerable deep-sea ecosystems, the answer is one or another version of 'probably not'. But the question itself is misleading; the desirability of such solutions can only be established in relation to their respective alternatives. This is why the tendency to frame such technological debates as confrontations between critics and proponents is perhaps inopportune: there are no proponents of solar geoengineering, but there are observers who doubt whether there are plausible alternatives for reaching international temperature targets by the end of the century. There are no proponents of releasing high-risk self-propagating artificial genetic elements into wild populations, though there are those that believe the world is running out of options for effectively protecting vulnerable ecosystems from invasive species.[53] Outside of the mining industry, enthusiasm for deep-sea mining is extremely limited, but there is growing awareness among politicians and scientists alike that a global transition towards environmental sustainability requires a safe and expanding supply of critical raw materials such as rare earth and platinum-group metals.[54] This is not a matter of being a proponent but rather of evaluating different decision alternatives that are all problematic in their own ways. In an ideal world, no risky, dangerous, or harmful technological solutions would be required because the problems which

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they are supposed to address would have been solved by other means. Unfortunately, this is not the world we live in.

Discounting the techno-fix thus requires confidence in the capacity of political institutions to deliver 'conventional' solutions to the global environmental crisis. There is not a lot of evidence that these capacities exist. Political failure is widespread and possibly systemic. The best that can be said about the results of decades of climate action at the highest political levels is that, in their absence, the world would be even farther from an emissions pathway consistent with 'safe' levels of global warming than it already is. For the protection of global biodiversity, two decadal strategic plans adopted by the parties to the Convention on Biological Diversity failed – not by narrow margins but decisively! Despite intense international regulatory efforts, the share of overexploited fish stocks keeps increasing. The world is not on track for reaching its environmental, agricultural, and developmental objectives under the 2030 Sustainable Development Goals.[55] The list goes on – although there are certainly also bright spots, where political efforts have delivered tangible improvements for the global environment. This is not in doubt. The point is, rather, that the empirical track record of political institutions is inconsistent with the trust that many observers place in them for delivering solutions for critical environmental challenges *without* relying on one or the other kind of techno-fix. It is a fundamental misconception to assume that political institutions and the outcomes which they deliver can easily be improved in line with what the scale of the problem demands. Most global environmental challenges have escalated over time, with the means that are required for their effective resolution accordingly becoming increasingly extravagant with every passing decade. If political institutions have already failed to deal with these challenges back when limited economic adjustments would have sufficed, why should they succeed now that a comprehensive restructuration of the entire global social and economic order is required? A high degree of plasticity is needed for what failed in the past to succeed in the future. Yet a pessimistic perspective suggests that behavioural patterns and the social structures that build on them are largely invariant over time: world leaders will not one morning wake up with the realization that, in the past, they have been unscrupulously privileging the interests of their countries (and particularly of powerful domestic interest groups) over the common good of present and future generations. Affluent citizens will not stop protesting against wind power projects in their vicinity that might depreciate their assets. Corporations will continue to primarily concern themselves with profit and will continue to cheat on pollution standards where it is opportune to do so. With invariance in human behaviour and derived social structures, the capacity of governments, international organizations, and other political institutions to make work what failed in the past is extremely limited, and TNTs might accordingly offer a potential fix. The problem cuts both ways, though: the past failures of political institutions to devise conventional solutions to the crisis does not mean they can easily be entrusted with the implementation of radical technological solutions. However, while the fix offered by TNTs will not make the fundamental limitations and deficits of global public policy disappear, it may reduce their severity. In that sense, the techno-fix is not a substitute for political solutions; rather, it might reduce the difficulty of devising them in the first place.

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