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Introduction

The destructive impacts of human activities on the global environment are as evident as the failure of adequate political response measures. While we may debate the nuances, the big picture is that we are facing an unfolding ecological crisis of civilizational dimensions. None of the core facts are in dispute: greenhouse gas emissions are on a trajectory which will lead to temperature increases that are unprecedented throughout all of human history, with concomitant effects on agricultural systems, sea levels, and the frequency and intensity of extreme weather events, while also posing the threat of triggering global catastrophe changes through self-reinforcing, non-linear changes in the climate system.[1] Oceans are under pressure from overfishing, waste dumping, oil spills, and pollution from land as well as from ships, in addition to the absorption of carbon into marine biomass threatening many marine life forms through higher acidity levels.[2] On land, industrialized agriculture is inflicting a heavy toll on the environment, as does the conversion of natural ecosystems into pasture lands for satisfying the ever-increasing global meat consumption and for growing feedstock.[3] Global biological diversity is being lost at rates that do not measure up to anything that has occurred in human history, forcing us to look back to major extinction events linked to asteroid impacts or large-scale volcanic eruptions in geological history for comparison.[4]

There is ample room for disagreement on details: how rapidly is biodiversity loss proceeding globally, regionally, and locally? Which fish stocks are at what exact risk of overfishing? For a given amount of carbon dioxide and other greenhouse gases that are emitted into the atmosphere, what are the precise effects on global average surface temperatures? What is the extent of marine microplastic pollution, and what are its consequences, including for human health? Things get more complicated once we factor in the future, which is arguably of greater interest in the contemporary political debate than the present. We need to rely on predictions and scenarios: what are the possible and probable future consequences of contemporary global environmental change? Which futures are preferable under various social, environmental, economic, and ethical vantage points, and how would we get there? How severely will future agricultural yields be affected by currently projected loss rates of insect biomass? How would the collapse of different fish stocks as a consequence of overfishing affect local communities and global food supply chains? How large (or narrow) is the time window for transitioning the global economy towards net-zero greenhouse gas emissions before dangerous levels of global warming become locked in? What is the technical and economic feasibility of a global phase-out of unsustainable petro-plastics and a phase-in of sustainable bioplastics?

Yet there is the risk of missing the forest for the trees. Notwithstanding the substantial uncertainties that surround the various environmental challenges and response options, in both the present and the future, it is safe to say that, without transformative action across all sectors of society and the global economy within a rapidly narrowing time window, the viability of contemporary civilization is at stake. This does not necessarily entail an imminent threat of the global socio-political order entering a terminal phase of rapid and comprehensive breakdown, but it is beyond reasonable doubt that critical parameters of the Earth system have entered, or are about to enter, the danger zone.[5] While the end-of-times narratives spun by contemporary radical activists may have debatable plausibility or limited probability, the environmental crisis is systemic, severe, and goes to the foundations of the present socio-economic order that includes fossil fuel consumption, aggressive resource extraction, environmental pollution, and invasive land system effects as distinguishing historical features. Estimating the precise severity of the crisis, its exact impacts across sectors or geographical regions, as well as its temporal expression, is fraught with difficulties of both a methodological nature and a conceptual one, as the future partially depends on actions that have not yet been taken and events that have not yet happened, notably including those that are effectively unpredictable. This also means that there is no straightforward recipe for devising an optimal global policy response. But, in the larger scheme of things, there is a clear and urgent need for transformative action.

This basic insight is not a matter of serious dispute. What we do see, however, is a remarkable degree of variation in the attitudes that politicians, scientists, activists, inventors, journalists, the business community, and the wider public hold towards the global environmental crisis. One end of the spectrum is home to apocalyptic visions of impending doom from imminent socio-ecological collapse, requiring a fundamental transformation of the capitalist mode of production and the unsustainable society–nature relation which it implies or, at the very least, invasive political responses that derive their legitimacy in large part from an alleged state of emergency that arises on the back of the environmental crisis. Policy preferences accordingly gravitate towards intrusive regulations and prohibitions. At the other end of the spectrum is the optimistic belief that human creativity and innovation will deliver effective (and typically also profitable) solutions to the environmental crisis. This entails a market-based approach, and governments should accordingly refrain from excessive regulatory intervention, although public funding and other types of support will nevertheless be welcome. Most stakeholders and observers will fall somewhere in between, seeing a lesser or a greater need for governments to put down the regulatory hammer and having differing degrees of confidence (or scepticism) regarding the prospects of timely and effective solutions through market-based innovation. With everyone arguably drawing on similar sets of facts, what explains this variation in attitudes? If there is no real disagreement on the big picture, meaning a systemic crisis in need of an urgent and comprehensive global response, why do perceptions vary from apocalyptic to optimistic, with policy preferences thus gravitating around disparate and largely incompatible conceptual clusters associated with either the reorganization of socio-economic order, immediate governmental emergency intervention, or a rather pedestrian model of market-based innovation with public support? Reasonable people will always disagree, including when it comes to the contemporary environmental crisis and the creation of a global response portfolio – but why do they disagree *that much*?

The answer, to a very large extent, revolves around divergent perspectives on the role of technology: in terms of the technological components of specific policy responses, but also for abstract considerations related to risk, controllability, and political power. Technology is what makes the difference between a world teetering on the brink of the abyss, a world in which human ingenuity solves the problems as they come and future generations look down with derision at the doomsayers of the present, and all worlds in between where human societies manage to muddle through the environmental crisis with varying degrees of success and dignity. Miracle innovations might make the environmental crisis disappear by sleight of hand. In a world with Terawatt-scale solar power, smart grids for efficient transmission and distribution, large-scale battery storage for solving the intermittency problem in renewable energy supply, and transportation running on clean electricity and green hydrogen, climate change would likely not be an issue. Parts of the global renewable energy supply would be directed towards the capture of carbon from ambient air (parts of which might be blended with hydrogen into synthetic fuels) and towards compensating residual emissions from sources, such as certain heavy industries, that are difficult to decarbonize. In parallel, we might also be drawing down atmospheric carbon dioxide through large-scale afforestation of genetically modified (GM) trees or algae designed to sequester carbon in their biomass with

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high degrees of efficiency. Having eliminated most carbon emissions, ocean acidification would cease to be a problem. With green hydrogen substituting for petrofuels, oil spills and operational vessel-source pollution would similarly stop being a threat to the marine environment. With global fish consumption at this point mainly being supplied from aquacultures using high-end gene technology for improving yield and nutritional value, and with advances in vaccine technology preventing the spread of harmful pathogens, fish stocks in the oceans would quickly recover. Simultaneously, the monitoring and enforcement of international rules on illegal, unreported, and unregulated fishing would benefit immensely from the use of high-tech satellites and other remote sensors, as would be the case in many other areas of global environmental governance. On land, we would reduce or eliminate the major drivers of biodiversity loss, including through novel biotechnologies that enable efficient genetic engineering at the scale of entire ecosystems, or that can undo extinction through the recreation of lost species. Copious amounts of rare earth elements, mined sustainably from the ocean floor, would ensure sufficient raw materials for the construction of the digital backbones of green and circular societies. Simultaneous improvements in resource efficiency and recycling would reduce aggregate demand for those and other raw materials, thus keeping the environmental footprint of the extractive industries in check.

Alternatively, the realization might dawn on us at some point during this century that these and other technological options face diverse practical problems ranging from challenging to insuperable. They might not be scalable to the extent that they have meaningful benefits in a global perspective. They might have unintended consequences that are harmful and might even go unnoticed until they are in widespread use and difficult to substitute. They might not be profitable enough to warrant commercial adoption because, perhaps, thermodynamic or other physical factors create a hard limit on the improvement of cost efficiency. Questions of social licence might impede technological development or diffusion, including through public backlash as a proxy for wider political and social conflicts and in cases where misinformation reduces the quality of the public debate. The political leadership of a major economy could unexpectedly pass to an individual with strong linkages to legacy industries keen to use the opportunity to maintain the profitability of their business models by having regulations put in place that reduce the competitiveness of sustainable technological alternatives. Inertia in the economic structure of the global car industry could mean that electric vehicles might fail to displace the internal combustion engine within a time frame that is relevant from the perspective of managing climate change. Unintended, unpredictable, and negative side effects might result from the use of experimental gene technology in the wild. Deep-sea mining could wreak havoc on marine ecosystems. Industrial GM fish production could offer a safe and effective contribution to solving the global challenges of global food security and overfishing, but limited customer acceptance might reduce commercial feasibility to zero. A global scale-up of renewable energy sources might entail intensifying opposition due to growing encroachment on the land rights of local communities. In the meantime, legacy industries would interfere with the transition towards a sustainable technological paradigm every step of the way by funding politicians, scientists, and think tanks that tamper with the political discourse by exaggerating the various costs, risks, and other negative impacts associated with that transition. This well-funded doubt, in turn, creates inertia in the political process and reduces the pace of change to below the threshold above which adjustments in some critical system parameters can still ensure a large degree of continuity in others. All of this suggests, at a broader level, that the role of technology for environmental sustainability cannot be reduced to questions of technical implementation and economic feasibility because 'politics' have a nasty tendency of getting in the way. Even from today's perspective, there is a convincing case that solutions which are both technically possible and commercially viable would, in principle, exist for most, if not all, global environmental challenges. The deficit in their implementation should not primarily lead us to conclude that the relevant decision-makers have insufficient will, capacity, or intellectual understanding. Although these factors certainly play their own role, it is important to take seriously problems of collective action and social organization that exist independently of whatever shortcomings may characterize individual cognition and behaviour. More broadly, the theoretical availability of far-reaching technical solutions in combination with the considerable deficit that is observable in their practical implementation suggests how problems of global environmental sustainability are primarily political in nature and cannot simply be engineered out of existence by innovating for optimal solutions ready for stakeholders to pick up at their leisure.

For better or worse, technology is a keystone in the contemporary and future politics of environmental sustainability. Its role, both as part of specific policy measures and in more abstract considerations of risk, human control capacities, or their potential to shift social and political power relations to sometimes considerable degrees, is typically a matter of debate and frequently a substantial bone of contention. There are three larger perspectives from which we may approach the issue. The first, and oldest, is rooted in economic liberalism, with its focus on market-based solutions to problems of environmental sustainability (and problems of human development more broadly). Human ingenuity and creativity filter through the economic incentives that operate on decentralized actors that compete in a given market environment, potentially leading to technological solutions that are commercially feasible while providing effective ways of dealing with the variegated contemporary sustainability challenges. Decentralization implies

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a need to ensure a proper directionality of market-based innovation, which means that this approach is primarily concerned with price signals. Research, development, and innovation for technologies with positive sustainability impacts, as well as their subsequent adoption and diffusion, all depend on the existence of price signals that are suitable for incentivizing profit-oriented actors to behave in ways consistent with the exogenous, political objective of transitioning to some form of global environmental sustainability during the course of this century. Technological solutions will emerge where it is profitable. Where it is not, governments may wish to interfere with price signals in order to ensure that the aggregate outcomes of decentralized action align with considerations of the public interest. This can include interference with the prices of specific products or services, it can entail the creation of entire markets in areas where none existed before, but it can also imply policy action for offsetting the potential effects on the international competitiveness of regulated entities from divergences in national regulations. Overall, though, the scope for complementary governmental interference is limited and the threat of harmful regulatory overreach implies a 'less-is-more' approach to public policy. At a broader level, this approach can thus also serve to legitimize inaction where it is opportune for legacy industries despite a clear rationale for public policy intervention.

The second perspective is the broad-brush criticism of technological innovation as 'techno-fixes' – that is, as inappropriate technological solutions to problems that are inherently political. The concept of the 'techno-fix' is crucial in the broader debate and I will reflect on it in more detail in Chapter 2. A crucial element of this second perspective is the underpinning assumption that powerful private actors, typically in the form of multinational companies or international philanthropies, are aggressively pushing towards technological solutions that entail unacceptable levels of risk, that are bound to intensify global inequities, that target the symptoms of unjust and unsustainable global power relations in order to sustain their existence, or a combination thereof. This perspective tends to be informed by neo-Marxism or critical theory more broadly, accordingly emphasizing the role of technology, and of its control and ownership, in the context of a global economic order that is inherently exploitative and where economic power structures, not simple interest group competition, is the chief determinant of public policy. Whereas the first perspective is characterized by a relative confidence in the ability of markets to deliver technological solutions that align with the public interest (presupposing functional markets and suitable incentives), this second perspective is mistrustful of the rhetoric that permeates the contemporary sustainability discourse both inside the UN and beyond, with all of the well-sounding talking points on climate justice, green economy, and agricultural resilience merely providing the façade that masks the primacy of power structures operating at a deeper level of social reality. The principal merit of this perspective is thus the centrality which it accords to questions of power that, perhaps, do not receive the attention they deserve from those that primarily chase public statements, position papers, and draft negotiation text at UN summits or countless stakeholder forums. Empirically, though, the conceptualization of technology in general, or techno-fixes in particular, as harmful, ineffective, or some sort of corporate ploy is not necessarily helpful. It is not entirely off the mark, for instance, to brand technological methods for drawing down atmospheric carbon dioxide as a techno-fix that prolongs the life of the fossil industry by enabling greater consumption of coal, oil, and natural gas than would otherwise be the case. Yet this also delegitimizes and trivializes a technological component that is indispensable for a global transition towards climate neutrality that attempts to keep in check macro-economic disruptions which, in the end, would likely have disproportionate impacts on vulnerable social groups and geographical regions. The question is also where to draw the line between techno-fixes, which are inherently problematic, and regular technologies, which are not. The structure of the global solar panel industry is an open invitation for considering some rather central questions of power in the politics of environmental sustainability. Yet few, if any, observers question the centrality of solar power in the transition towards climate neutrality on the grounds of the Chinese supremacy that has come to characterize the industry. While there is arguably insufficient attention given to foundational questions of power in the contemporary discussion on global environmental governance as such, these questions are not necessarily linked to the problem of constructing a global policy portfolio that allows for a fair and effective response to the environmental crisis.

The third perspective, and the one that I adopt in this book, aims for a middle-ground approach to the problem of technology in the global politics of environmental sustainability against the background of a large and diffuse body of literature that emphasizes the embedded nature of technology in various types of social structures.[6] The benefits or harms that a technology creates, the variation of its impacts across social groups or geographical contexts, its alignment with wider social values and political objectives and, in a sense, its very nature as such, are all underdetermined at the level of its technical characteristics as a physical artefact. What it is and what it does depends to a non-trivial degree on its social context and thus on its political regulation at various scales that include international institutions. Technology is thus neither intrinsically beneficial or harmful nor is it intrinsically sustainable or unsustainable; its wider political significance ultimately emerges only through its interaction with a given social and regulatory context. Spontaneous market operations rarely lead to technological outcomes with significant social benefits by themselves, just as the combination of human creativity and profit-orientation is usually not sufficient

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for the development of risk technologies in ways that are reasonably safe. With the social purpose of technology being co-determined by regulation and other, more abstract social structures, its developers or owners have limited scope for strategic instrumentalization. At the same time, technology can have crucial implications beyond a specific policy context and cause wider, systemic effects that may sometimes result from strategic agency, although typically being both unintended and unanticipated. Power matters, in other words, but humans and human organizations are limited in their capacity to control, predict, and direct social change, whether through technological means or otherwise. For purposes of environmental sustainability, technology is an essential component for transitioning the planet and its inhabitants towards safe long-term parameters. At the same time, the social propensity towards hype cycles should factor into technology assessment and the predilection of novelty should be borne in mind as a potentially important bias when evaluating the relative merits of novel technological options relative to conventional regulatory options, possibly in combination with technological elements that are decidedly pedestrian in nature when compared to their new and flashy alternatives. With technology being indispensable for any policy package that might credibly be understood as a fair and effective response to the global environmental crisis, there is a need to be cognizant of the diverse social, political, and environmental risks that technological solutions may entail, although we should refrain from stigmatization and we should commit to the comprehensive scientific assessment of novel technological options to enable high-quality deliberation and decision-making while, at the same time, understanding and perhaps safeguarding against the potential risk of scientific research locking-in the future deployment of technologies understood to entail risks that appear unreasonable in the context of abstract and collectively shared understandings of what amounts to the public interest. Such an ambiguous and somewhat agnostic middle-ground approach does not provide an epistemological position that is necessarily superior to alternative ways of looking at the problem from positions that are closer to the edges of either 'pro-tech' or 'anti-tech'. Less than a matter of epistemological non-commitment, this choice intends to account for the pervasive ambiguities that are a defining element of global politics at the interface between environmental sustainability and technology as well as of its diverse scientific, technical, normative, and legal subcomponents. With the key concepts of 'technology' and 'environmental sustainability' additionally referring to entities of considerable plasticity and distinct temporality due to the crucial role of anticipatory decision-making in the present, subject to constraints that result from past choices and in regards to a future that is distant, uncertain, and indeterminate, the object of interest itself indicates the need to adopt an open-ended approach that seeks to navigate a middle ground between a 'pro-tech' Scylla and its 'anti-tech' Charybdis.

It is time to introduce a crucial caveat into a discussion that, so far, has referred to 'technology' in a rather undifferentiated and abstract manner. Many of the theoretical points that I elaborate in this book are likely applicable to technology as such, subject to various smaller or larger conceptual adjustments. However, this book does not deal with technology in a general sense, but rather with what I refer to as 'transformative novel technologies' (TNTs). These technologies are 'transformative' in the sense that they are understood to grant significant leverage for tampering with the global environment as well as society–nature relations, in both good and bad ways. Their costs are low relative to their potential effects – substantially lower, that is, than the costs of alternative solutions, whether these be purely regulatory in nature or involve a conventional technological component. The 'novelty' of TNTs resides in their emergent nature: some are in the early stages of deployment; others remain, for now, in the research, development, and innovation pipeline; and still others are largely speculative and exist more in the minds of scientists and inventors than in the real world. TNTs are thus fluid, ambiguous, uncertain, and open-ended in nature. While they are understood to hold enormous potential for causing both beneficial and harmful impacts at a considerable scale, this may not turn out to be the case for some or even a majority. This includes those few TNTs that are already in the early stages of deployment, adoption, and diffusion, whether as pilot projects for atmospheric carbon dioxide removal or in somewhat more established form in the bioinformatical utilization of digital sequence information. However, notwithstanding the human tendency to overestimate the eventual relevance of new and emerging technologies, and bearing in mind the limited human predictive capacity even for time horizons below the multi-decadal scale, contemporary observers broadly agree on the game-changing potential of the TNTs that are the empirical focus of this book, with expectations that are likely lower for the mining of critical resources in areas beyond national jurisdiction, particularly in Antarctica, than for the two other broad technological which I consider here. Both their transformative potential and their novelty make TNTs an important issue from a perspective of environmental sustainability: they might offer feasible alternatives to the apparent systemic failure to respond to the environmental crisis with conventional means, but they might also be a dangerous distraction or even turn out to be harmful in an immediate sense. This, to some extent, we do not know and cannot know in advance due to their plasticity and ambiguity. Whether they turn out to be potential solutions, potential problems, or ultimately irrelevant depends on future research, development, and innovation, as well as the abstract and evolving framing of technology in the politics of environmental sustainability. It also depends on the rules, in terms of both operational regulatory frameworks and abstract norms and principles, that shape their gradual emergence. The future role of TNTs in the global politics of environmental sustainability, largely indeterminate in the present, thus depends in part on the design of contemporary governance frameworks. This, in turn, requires forward-looking engagement from both scholars and practitioners. Making TNTs work for environmental sustainability in the future, or averting the diverse harms that they may end up causing, requires early buy-in so that regulatory frameworks can coevolve with technological development.

Technologies are typically regulated at different scales in parallel, from the local to the global, and from sources that may be public, private, or hybrid. The specific focus of this book is on the regulation of TNTs through international institutions – that is, formal intergovernmental rule systems created and operated by states with a view to the realization of mutually beneficial cooperative outcomes. Such international institutions can play different and specific roles in technology regulation, and TNTs have specific linkages to their core purpose of unlocking joint cooperative gains from international cooperation in situations where collective action problems would otherwise lead to inferior outcomes, including cooperation failure. From the outset, the scale of their impacts and their corresponding transboundary implications turn TNTs into an object of interest from a perspective of international cooperation: they may entail potential benefits that cannot be unlocked without appropriate arrangements for ensuring smooth international cooperation, just as the transboundary risks and negative externalities which they may entail can require intergovernmental arrangements for ensuring adequate cooperation on matters of mitigation, risk assessment and management, or compensation for transboundary harm. The regulation of TNTs through international institutions accordingly affects the aggregate production of gains, costs, and risks, as well as their international distribution. The regulatory reach of international institutions is limited due to well-known challenges of international law, including the absence of effective capacities for the enforcement of international legal obligations. Technology regulation through international institutions also tends to be sparse when compared to the density and precision of rules that frequently characterize regulatory frameworks at the domestic level. Yet international institutions are also both unique and indispensable in that they provide a channel for states to address TNTs and other technologies from the specific vantage point of the diverse cross-border implications which they may entail. And while there is increasing scholarly and practical interest in transnational forms of governance that entail cross-border cooperation that extends beyond traditional government-to-government relations, the narrow (albeit specific) functions which international institutions can provide make them an indispensable component in the broader regulatory complexes that exist across scales and across the public–private divide. And while transnational governance instruments, such as voluntary industry commitments or scientific codes of conduct, are increasing both in their empirical prominence and in the academic attention which they command,[7] formal intergovernmental arrangements are indispensable for the assessment and monitoring of activities with cross-border impacts; for avoiding regulatory races to the bottom through the provision of international minimum standards; for reducing red tape and for facilitating technology transfer; for ensuring the supply of technologies or their associated benefits as global public goods; for ensuring fairness, equity, and legitimacy in global politics; and for many other functions that cannot readily be provided at other scales and from other sources.

I start from the broad analytical distinction between the latent 'promises' and 'perils' that can be associated with different technologies in different configurations. The role of institutions is quite simply to contribute to the realization of promises and to the avoidance of perils. International institutions, in other words, help states in achieving beneficial outcomes and in averting detrimental outcomes associated with a technology. What exactly is beneficial or detrimental to whom, and by how much, will often be contested. The specific typology which I develop, without necessarily claiming completeness or exhaustiveness, is simply a broad framework for thinking about technology, as well as its relation to international institutions and cooperation, in a systematic manner. This framework entails three promises and three perils that can be associated, in different configurations, with different TNTs in the environmental domain. The first promise is *impact management*: the capacity of TNTs to reduce harmful anthropogenic impacts on the environment, harmful environmental impacts on human societies, or both. The second is the *information commons*: the creation, collection, and unrestricted provision of information for scientific and other purposes with potentially significant socio-environmental benefits.[8] The third is the *reduction of global injustice*: the supply of resources or capacities to groups that have particularly pronounced vulnerabilities to processes of global environmental change or that possess specific developmental needs in the context of environmental sustainability. Among the perils, the first is quite simply *environmental harm*: negative impacts on the environment that originate from a TNT in either a transboundary context or with regard to areas that are beyond the scope of national jurisdiction yet of common concern. The second peril is the *crowding out of feasible alternatives*. Sometimes incorrectly referred to as 'moral hazard' in contemporary debates on climate engineering, this peril consists in the false present-day belief that TNTs will offer efficient solutions to the challenges of environmental sustainability in the future and that, accordingly, present-day policies should be designed under the assumption that these TNTs will become available in the future at scale, in a manner that is economically feasible, environmentally sound, and socially accepted. These policies fail to the extent that this assumption eventually turns out to be wrong. The third peril is the *aggravation of global injustice*: just as TNTs may mitigate injustice, they can also intensify it by allocating harm to vulnerable groups or to societies that are already suffering from socio-economic underdevelopment as a result of various historical injustices, or by depriving them of benefits to which they are legally or morally entitled.

The promises and perils associated with TNTs provide the context in which I discuss international institutions, both analytically and normatively. Analytically, promises and perils are connected with various challenges that characterize international cooperation through formal institutions. Sometimes these promises and perils tend to be zero-sum across states with diverse and frequently incompatible interests: if some states stand to gain from a technology, others are bound to lose. Sometimes there is ample scope for states to achieve joint gains from institutional responses, meaning genuine win–win situations. The challenges of international cooperation are not trivial either way, although they are significantly more accentuated in the former case than in the latter. We can also see how the ways in which various technological promises and perils fit into pre-existing regulatory structures at the international level greatly influences the ways in which institutions can process them: some novel technological issues are similar (or comparable) to problems that international institutions are already dealing with and can thus easily be accommodated. Other issues might be so disparate that there is no intuitive way of handling them. Finally, there is also the question of how well such issues are understood. Typically straddling the boundary between 'science' and 'politics', some of the promises and perils linked to TNTs can be defined and operationalized with relative ease, whereas others are diffuse, ambiguous, and difficult to turn into actionable political agenda items. Aside from all of these considerations is the normative dimension: disregarding the diverse political challenges that states face in grappling with TNTs through formal international institutions, there is also a need to consider how, in theory at least, we might design 'better' institutional responses – in the sense of unlocking greater capacities for the realization of technological promises and for the avoidance of technological perils without – and this is a central point – succumbing to the frequent trade-offs that may present themselves between different types of promises and perils. In some sense, and this is an issue to which I will return in Chapter 7, the key to 'better' international regulation is the differentiation between those trade-offs that are intrinsic to a TNT and those that are a result of problematic institutional designs. The latter can be overcome through institutional adjustments, whereas the former are unsurmountable except through processes of socio-technical change that, to a large extent, are outside of the immediate influence of international institutions.

At the core of this text are thus four questions: First, *how are international institutions responding* to the promises and perils associated with TNTs? This question is about the contributions which different institutions make to the realization of promises and the avoidance of perils. How effective, in other words, are institutions in leveraging TNTs for environmental sustainability while preventing them from creating new and distinct challenges of their own? Second and third, *when* do international institutions respond to the promises and perils associated with TNTs, and *why do they do so in different ways*? This question accordingly has two elements: on the one hand, we need to understand the conditions under which international institutions do, and do not, respond to new technological challenges. Why are there responses to *some* kinds of problems but not to others? On the other hand, when institutions *do* respond, we need to account for the observable variation. Why do institutional responses sometimes have a narrow focus on specific technological aspects and sometimes a broad and comprehensive scope? Why do they sometimes amount to little more than unspecific and non-binding political declarations and sometimes entail specific, binding, and enforceable international legal obligations? While my theoretical argument is broadly situated within regime theory,[9] I approach these two aspects from three different conceptual angles: international constellations of state interests, the normative fit between novel technological issues and pre-existing regulatory structures, and the constitution of technologies as governance objects. These three perspectives offer conceptual lenses that can elucidate different aspects of the complex international politics of TNTs. Fourth, and finally, I ask how international institutions *should* respond – that is, how they might be able to capture larger shares of technological promises while being more effective at avoiding technological perils. This analysis faces a particular challenge from the existence of trade-offs: the realization of promises might sometimes entail the manifestation of perils, just as the avoidance of perils might sometimes require foregoing some promises. This is a central conundrum which has vastly complicated, and possibly even polarized, academic debates on TNTs in the context of environmental sustainability. Without pretending to have solved this central puzzle, I approach the question of desirable institutional responses with the assumption that some, but not all, trade-offs between promises and perils might be situated at the level of institutions and not the level of technology. This means that, in some cases, smart institutional design might enable the management or even elimination of trade-offs.

Empirically, the text centres on three wider technological domains, the specific TNTs which they entail, and the international institutions within the respective issue areas. The first of these domains is *biotechnology*. Here, recent disruptive innovations in gene editing technology, notably in the form of the CRISPR/Cas9 system, are revolutionizing genetic engineering. Advances in sequencing technology are enabling the faster, cheaper, and more precise readout of genetic information. The advent of big data analytics leads to the storage of genetic information in gigantic digital libraries suitable for large-scale computational analyses. The confluence of these developments enables applications with significant potential for contributing to environmental sustainability while also raising a variety of challenges. Gene drive technology biases inheritance patterns and thus allows target genes to be rapidly ‘driven’ through populations of species with short reproductive cycles.[10] Gene drives would allow the suppression or elimination of disease vectors such as mosquitoes, or of invasive species that threaten agricultural systems or vulnerable ecosystems. This may provide a high-impact solution for a crucial driver of biodiversity loss and help resolve a variety of associated social and environmental challenges.[11] Yet it also raises unprecedented biosafety issues to which existing rules and procedures on risk assessment and risk management cannot feasibly be applied.[12] Other applications, such as de-extinction or Horizontal Environmental Genetic Alteration Agents, are similarly problematic.[13] Bioinformatics – the analysis of genetic sequence data stored in vast digital libraries via big data analytics – could make major contributions to biodiversity conservation, for instance by providing large-scale and high-precision genetic analyses for enhanced conservation policies but also by storing digital backup copies to hedge against the risk of extinction. Yet in this and various other contexts, the storage and utilization of digital sequence information poses serious threats to established norms and regulations meant to channel back some of the commercial and other benefits associated with genetic resources to those individuals, communities, and countries that have conserved and stewarded them for the greater good of humanity at large. While open-access utilization of digital sequence information provides indirect and diffuse global public goods, it also undermines established norms of fairness and equity while undercutting the direct transfer of financial and other assets for the support of environmental policies in developing countries and least-developed countries.[14]

I broadly refer to the second technological domain as *climate engineering*. This term, as well as the similar term ‘geoengineering’, has recently gone somewhat out of fashion as some observers consider it an inappropriate umbrella term for two technological categories that purportedly differ fundamentally in purpose, aggregate risk, and governance implications.[15] Negative emissions technologies, for the removal and permanent storage of atmospheric carbon dioxide, constitute one of these categories. Originally an obscure academic niche issue, today these technologies are a critical and indispensable element of global climate policy. Virtually every contemporary emissions pathway consistent with levels of global warming that are politically and scientifically considered as safe requires large-scale removals of atmospheric carbon dioxide during the second half of the twenty-first century or earlier.[16] The necessary removals are typically estimated to be somewhere between 3 and 10 gigatons (Gt) of carbon dioxide per year. Some proposed methods would combine bioenergy with technology that captures carbon dioxide emissions at point sources and subsequently stores it in perpetuity, an approach originally conceived for eliminating carbon dioxide emissions from fossil power stations. However, more than two decades of research and development have not delivered cost reductions that would make the technology commercially viable at the global scale. The same applies to an alternative technological approach that directly captures carbon dioxide from ambient air, an area presently seeing a vast upswing in commercial interest.[17] While these technologies are part of the contemporary policy mainstream, proposed interventions that would induce an artificial global cooling effect, sometimes referred to as 'solar radiation management' or 'solar geoengineering', are much more controversial. By injecting reflective particles into the stratosphere, by brightening marine cloud formations, or by thinning high-altitude cirrus clouds, this approach would directly interfere with the planetary radiation budget, offering a low-cost solution for the immediate reduction or elimination of global warming, as well as a measure of last resort for responding to the sudden and catastrophic disruptions that could result when anthropogenic pressure breaches unquantified thresholds in the climate system triggering nonlinear responses.[18] Yet solar geoengineering also entails numerous and severe risks, likely including the 'unknown unknowns' of unpredictable yet possibly dramatic consequences of large-scale tinkering with the planetary radiation balance. Solar geoengineering and negative emissions technologies both pose significant social, environmental, and political risks. Curiously, the former is widely understood as a taboo whereas the latter underwent extensive normalization until it became a fact of life.

The third domain is *mining beyond national jurisdiction*. Minerals, from rare earth elements to platinum-group metals, are indispensable raw materials in the contemporary world economy. They are used for manufacturing products that range from electronic devices to hardened concrete, with substitutes usually not available. The concentration of these minerals in terrestrial deposits is low, making them difficult to mine and expensive to buy. Extractive operations have a significant environmental footprint and frequently cause concerns regarding the rights of workers and local communities. These minerals are also central for the global sustainability transition, notably in the production of key clean energy technologies.[19] Both the deep seas and near-Earth asteroids, as well as possibly Antarctica, contain significant deposits of these minerals. The volumes and concentrations of these deposits is possibly of a magnitude whereby a handful of extraction operations could displace the entire terrestrial mining industry, reducing environmental impacts and social harm while providing crucial raw materials for the global sustainability transition. However, mining in these areas presents perils, notably in the form of environmental harm. The deep sea contains highly vulnerable species and ecosystems, mostly scientifically unexplored and prone to adverse impacts from mining operations. Antarctica is a fragile ecosystem of crucial importance for the global environment. Asteroid mining poses both terrestrial and extraterrestrial environmental threats, for instance from extraction via blast mining or from accidents during transit and transportation. For the deep seas and Antarctica as well as for asteroids, mining operations can have crucial implications for established norms related to fairness and equity, similar to the case of digital sequence information mentioned earlier.[20]

In Chapter 2, I start with a broad discussion of the linkages between technology and environmental sustainability, attempting to navigate a 'middle ground' along the lines discussed earlier. I then introduce 'promises' and 'perils' as the central elements of my conceptual framework. Chapter 3 elaborates on the role of institutions. At the core of this chapter are three guiding questions: how do international institutions respond to the emergence of TNTs? When do they respond and why do they do so in different ways? How should they respond? Chapters 4 to 6 address the domains of biotechnology, climate engineering, and mineral extraction, respectively, beyond national jurisdiction. I first parse the associated promises and perils before delving into the respective institutional responses, conceptualizing them in terms of scope and depth and identifying observable and non-observable yet plausible instances of non-responses. The assessment of institutional responses along these lines allows for a rough approximation of the extent to which they facilitate the realization of technological promises and the avoidance of technological perils. Afterwards, I discuss how international constellations of interest, normative fit, and governance object constitution each explain the conditions under which responses do (and do not) happen, as well as the variation between those that do. I conclude each chapter with an issue-specific discussion of hypothetical institutional alternatives that might enable the realization of promises and the avoidance of perils with greater effectiveness. Chapter 7 synthesizes the overall findings; expands on the role of normative fit which, to preview an important result, has substantial explanatory power for the conditions under which institutions respond as well as for the variation in responses; and expands on several latent themes: the regulatory choice between moratoria and controlled use, the management of trade-offs, as well as the role of path dependence. Chapter 7 concludes with some tentative thoughts on how the argument developed here might extend beyond the environmental domain.

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Notes

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