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Climate Engineering

Without any doubt, climate change is *the* dominant contemporary environmental challenge. The core facts are straightforward: First, greenhouse gases trap heat by blocking the solar radiation which the planet's surface reflects back into space. Second, increasing anthropogenic emissions since the beginning of the Industrial Revolution are causing temperature anomalies that lead to significant and potentially irreversible and uncontrollable disruptions to the Earth system as such. Third, these emissions originate from sectors that are central to global socio-economic development and thus cannot easily be abated without touching on fundamental questions of social and economic order. Fourth, the long atmospheric half-life of some greenhouse gases, notably carbon dioxide, makes climate change inert, meaning that the effects of emission reductions in the present play out over decades. Mitigation thus creates benefits from avoided climate change that stretch out into the future while creating costs that concentrate in the present, leading to complex economic, political, and ethical questions on how to weigh present costs against future benefits.[1]

As the Intergovernmental Panel on Climate Change (IPCC) puts it in its 2022 assessment report, 'it is unequivocal that human influence has warmed the atmosphere, ocean and land'. This has already resulted in '[w]idespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere'.[2] At the same time, most of the harmful impacts of climate change still lie ahead. These impacts are best understood as *risks* with associated probabilities that increase as global warming intensifies.[3] The types and degrees of risks that societies are willing to accept is ultimately a normative issue. Similarly, there is no objective answer to how we should discount future gains and losses in relation to the present. It is thus impossible to define a precise cut-off point beyond which global temperature increases are

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objectively too large. That being said, the broad scientific consensus is that an increase in global average surface temperatures of more than 1.5°C between (roughly) the mid-nineteenth century and the end of the twenty-first century would create risks that are socially unacceptable and partially unmanageable. These risks exist in three categories. First, slow-onset events gradually ramp up pressure on human societies and the environment. These include increasing sea-level rises that threaten coastal areas and small island states, shifts in regional temperatures or rainfall patterns that interfere with global food production, and accumulating harm to marine ecosystems as the oceans absorb more and more carbon dioxide and thus become more acidic. Second, global warming leads to an intensification of extreme weather events.[4] As global warming proceeds, the effects of droughts on agricultural systems become more severe, heat waves cause greater numbers of casualties, and forest fires spread more rapidly, among others. Third, non-linear responses in the Earth system could lead to rapid, self-reinforcing, and uncontrollable global changes as a result of atmospheric greenhouse gas concentrations increasing beyond some unquantified threshold. Across all three categories, risks scale with global emissions and become 'increasingly complex and more difficult to manage'.[5]

Between 1990 and 2021, annual global emissions of carbon dioxide and equivalent greenhouse gases almost doubled, to just under 60 $GtCO_2e$. Carbon dioxide accounts for about two-thirds of global emissions, with energy-related carbon dioxide emissions alone accounting for about half of the total. Land use, land-use change, and forestry are other major sources, with various human activities leading to the atmospheric release of carbon previously bound in organic matter.[6] The second largest impact on global warming comes from methane emissions from sources such as cattle farming, waste, or natural gas extraction. In contrast to carbon dioxide, methane has a short atmospheric half-life of about nine years and is thus classified as a short-lived climate pollutant. The corollary is that mitigation produces tangible benefits over relatively short time frames and thus limits the detrimental effects of temporal discounting on climate action and international cooperation.[7] Nitrous oxide is presently emitted at an annual volume equivalent to about 2.7 Gt of carbon dioxide and accounts for 4 per cent of total global emissions. Its sources include agricultural activities, fuel combustion, and wastewater treatment. Fluorinated greenhouse gases, finally, are emitted from certain refrigeration systems, manufacturing processes, or specific solvents or aerosols. They are extremely powerful climate forcers, notably including sulphur hexafluoride, one unit of which is equivalent to almost 24,000 units of carbon dioxide, as the most-powerful anthropogenic greenhouse gas in existence. Due to their low emissions volume, however, they currently account for only about 2 per cent of the global total.

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Notwithstanding this diversity of greenhouse gases and emissions sources, climate change is primarily a carbon dioxide problem, and carbon dioxide is primarily an energy problem. More than with any other greenhouse gas, carbon dioxide emissions are intrinsically bound up with the history of human civilization since the mid-nineteenth century. Historically, fossil fuels have been a major factor for the transition from agricultural to industrial societies; for the naval supremacy that formed the foundation of *Pax Britannica* throughout the nineteenth century and up to World War I; for socio-economic underdevelopment and endemic political instability in oil-rich regions, particularly the Middle East; and for the emergence of democracy in the West.[8] Carbon dioxide is not just an environmental pollutant: it is a key element of the trajectory that human civilization has been following for two centuries. The history of fossil fuels and carbon dioxide emissions is thus also the history of world order, allowing the countries of the Global North to experience unprecedented economic development which they then leveraged for political power over the countries of the Global South. The costs of fossil-fuelled development only became apparent much later, when the scientific understanding of the causes and consequences of the greenhouse effect began to improve from the 1970s onwards. The following two or three decades saw increasing political awareness of the existence of a hard limit to the volume of greenhouse gases that human societies can emit without causing unacceptable and possibly unmanageable harm. As a corollary, the path towards prosperity previously taken by the Global North turned out to be closed for the Global South. Until the present day, questions of historical responsibility and differentiation between industrialized and developing countries continue to be major stumbling blocks in international climate diplomacy, even as the cumulative emissions of North America and Western Europe are declining relative to those of the new economic powerhouses of the Global South, first and foremost China.

Beyond energy from fossil fuel combustion, emissions of carbon dioxide, methane, and nitrous oxide also track the history of global agricultural transformation and extractivist development. The emergence of agrochemicals during the early twentieth century, the subsequent advent of novel plant breeding techniques, the transition towards industrial agriculture, and the substantial expansion of global acreage all contributed to the drastic rise of global emissions. In some parts of the developing world, the push for economic modernization led to significant deforestation and other land use changes, translating into large atmospheric releases of carbon previously bound in biomass. Similar to energy, these and related developments are central to the emergence of contemporary societies. At the same time, the global land system complex generates harmful non-climate effects for humans and the environment that are significantly more pronounced than is the case for the global energy system. However, there are few feasible options for mitigating land

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system-related greenhouse gas emissions without causing negative impacts on global food production or, in some cases of forest carbon management, without affecting the rights and livelihoods of local communities.

Thus, while climate change creates risks of different types and magnitudes that imply an urgent need for rapid and comprehensive action, greenhouse gas emissions are largely integral to broader social structures and thus difficult to mitigate, especially considering that decades of political negligence have led to a drastic escalation in problem severity. As atmospheric greenhouse gas stocks kept building up, the reduction pathways for preventing dangerous levels of global warming became steeper and steeper. In order to reach a 'safe' global warming target of 1.5°C by the end of the century without temporary overshoots, global carbon dioxide emissions must decline by about 45 per cent by 2030 relative to their level in 2010. Not accounting for emissions from the land system, this means that the world roughly requires a 17 Gt reduction in annual industrial- and energy-related carbon dioxide emissions in less than a decade. A short-term reduction of this magnitude is wildly out of touch with the historical trajectory of almost continuous emissions growth with rare interruptions from global wildcard events such as the 2009–10 financial crisis or the 2020 impacts of the COVID-19 pandemic and governmental response measures. Yet decades of failure to shift the world onto a safe emissions trajectory cannot simply be explained in terms of the moral failure of the relevant decision-makers (although this certainly is a part of the story). There are other factors at play. One is a basic collective action problem. Greenhouse gas emissions from fossil fuel combustion, deforestation, and various other sources create specific and direct economic benefits for users but diffuse global costs through climate change. Whereas states accordingly have an interest in the prevention of harm as a consequence of climate change, they are also aware of the immediate and tangible benefits which they obtain from activities that are causing the climate to change in the first place. As a consequence, states have an incentive to undermitigate while freeriding on the mitigation efforts made by others. Another factor is the persistence of behavioural patterns, particularly regarding individual consumption. Individuals, including those that form part of the electorate of major emitter countries, are typically unwilling to incur costs and inconveniences at a level consistent with their respective problem perceptions. Finally, there is also the role of disinformation and propaganda, particularly during the 1990s and 2000s, when interest groups from the fossil fuel sector, particularly in the United States, attempted to discredit climate science in order to prevent potential regulatory outcomes that would slash corporate profits – despite parts of the industry, at that point, having been privately aware of the problem for decades!

Incentive structures, behavioural patterns, and disinformation, but also a lack of political courage and a wide range of other factors, have created a situation in

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which safe levels of global warming require rapid, transformative, and global action on an unprecedented scale. In many ways, we are already seeing the seeds of a future transition towards climate neutrality, as the economics of low-carbon development continue to improve. Increasingly, the moral case for climate action is being replaced with a business case. Advances in diverse low-carbon technologies, changing consumer preferences as well as a changing regulatory environment all imply that climate action is increasingly driven by commercial self-interests rather than normative commitments towards the future well-being of human societies. The energy sector in particular has seen extraordinary increases, across different geographical regions, in the competitiveness of wind and solar power relative to coal and natural gas. In some parts of the world, electric vehicles have turned from niche products into social status markers for affluent urban elites. Innovations in areas such as battery storage, hydrogen, smart electricity grids, low-carbon urban transportation, software for personal carbon accounting, and many others indicate that a fundamental socio-economic shift is underway, at least in some regions. And, while the market environment for low-carbon technologies and business models continues to improve, governments are, for the most part, becoming more sincere and ambitious in their commitments to reducing, and ultimately eliminating, global greenhouse gas emissions.

But it will not be enough. Despite notable (and partially surprising) recent increases in commercial interest, political ambition, and social awareness, past negligence has created a mitigation burden that cannot be served in the present without putting the axe on the foundations of globalized market civilization.[9] In other words, safe levels of global warming can no longer be achieved by reducing emissions at a scale and speed that upholds the system integrity of the global economic order. And this, finally, brings us to climate engineering – that is, the 'deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and its impacts'.[10]

Climate engineering, also referred to as geoengineering, is a somewhat vague umbrella term for various technologies at different levels of readiness. In recent years, the political and academic debate has moved away from this umbrella term due to its supposedly misleading aggregation of two separate technological fields that differ in purpose, risk profiles, and governance implications. As I shall argue, this disaggregation is not without problems. Yet, even without necessarily abandoning the overarching label of 'climate engineering', we need to acknowledge the distinction between negative emissions technologies (NETs) and solar geoengineering (SG). The terminology may vary, with NETs sometimes referred to as methods for carbon dioxide removal, and SG being termed solar radiation management or albedo modification, among others.

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NETs, to start with, are a suite of natural, technological, and hybrid solutions, at various stages of readiness and with varying degrees of feasibility, for the removal and long-term storage of atmospheric carbon dioxide. NETs, in other words, pull carbon dioxide from the atmosphere. A large-scale deployment of NETs in the future eases the mitigation burden in the present. That is, if there are technically and economically feasible methods to reduce atmospheric carbon stocks in the future, emissions mitigation becomes less demanding (and costly) in the present. In one sense, this buys us more time for the global transition towards climate neutrality. Safe levels of global warming may thus be achieved without painful, disruptive, and costly mitigation efforts. In another sense, NETs could compensate for residual emissions from sectors that lack technically and economically feasible zero-emissions options. This might include shipping and aviation, where electrification is presently unlikely to be viable and alternatives such as synthetic fuels or biofuels would likely produce complicated spin-off challenges. NETs could also offset carbon emissions from aluminium, steel, and cement production, sectors central to global infrastructure development yet currently without realistic prospects for decarbonization. In the global land system, emissions reductions would, among others, require comprehensive regulatory reforms for curbing deforestation, particularly in developing countries, as well as profound changes in dietary habits for bringing down meat consumption and its associated emissions. Finally, in the energy sector, NETs could offset residual consumption of natural gas, thus providing more time for transitioning to a 100 per cent renewables power system incorporating complex, additional components, such as large-scale battery storage, for solving the intermittency problem. NETs, in other words, offer a potential solution to the problem that the technical and economic feasibility of transitioning towards zero-emissions models is lower in some sectors than in others. Even in energy, where the prospects of decarbonization are particular strong, NETs would unlock the possibility of time-limited natural gas consumption for serving specific niche functions while the world continues its transition towards 100 per cent renewables.

In recent years, three specific types of NETs have stood out in the political and academic debate, with the perceptions of their respective feasibility shifting strongly over time. The first type, possibly counterintuitive to describe as a ‘technology’, is simply biomass for the sequestration and storage of carbon dioxide. Such biomass, for instance in the shape of large-scale global afforestation programmes, are typically understood as ‘natural’, rather than ‘technological’, solutions. This point is debatable: any programme for large-scale carbon sequestration and storage in biomass entails distinct technological aspects, such as relating to the organization, engineering, and design of tree plantations in ways consistent with regulatory requirements regarding the measurability and verifiability of carbon

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removals.[11] Moreover, genetic engineering or other novel plant breeding techniques would likely be indispensable for ensuring rapid biomass growth and maximal carbon sequestration, as well as resilience to environmental stress in order to contribute to the permanence of carbon storage. While framing such programmes as a 'natural' solution is likely to be beneficial in terms of the social licence to operate, it does not do justice to their hybrid nature that includes distinct technological elements. Estimates vary regarding the global potential for carbon drawdown through forestry programmes. Some studies consider removals in the order of hundreds of gigatons as feasible – an order of magnitude that could offset global greenhouse gas emissions in their entirety for several years.[12] Other studies arrive at less sanguine conclusions and grant forest-based measures an at best secondary role in any future NETs portfolio. Beyond forests, marine biomass offers another option for hybrid natural-technological removal of atmospheric carbon dioxide. Specifically, the artificial stimulation of phytoplankton growth has been considered as a method for large-scale marine carbon sequestration – yet one that has been going out of fashion due to the expected harmful impacts on the marine environment as well as limited overall sequestration capacity.[13]

The second major type is the combination of bioenergy with carbon capture and storage (BECCS). In principle, this can entail different types of technical implementation. The most common concept revolves around two elements. In a first step, dedicated crops are cultivated for energy production, binding atmospheric carbon in their biomass as they grow. In a second step, these plants are combusted in specialized power stations in order to produce energy. Normally, this would imply that the carbon that was previously bound in biomass is re-released into the atmosphere. By using CCS technology, however, the carbon dioxide is separated from the flue stream and brought into long-term storage within geological formations or other appropriate settings. BECCS thus amounts to what, in Germany, is colloquially referred to as a pig producing egg, wool, and milk: providing energy while simultaneously drawing down atmospheric carbon dioxide. At the same time, there are significant concerns about BECCS that have caused the approach to fall out of favour in recent years. The deployment of BECCS at large or even moderate scales would imply drastic changes in the global land system.[14] Requiring a substantial share of global acreage to be converted from food crops to energy crops, this implies severe risks for food safety and sustainable development more broadly.[15] In principle, BECCS can also be implemented by hooking up CCS technology to existing biomass flows, for instance in the context of waste incineration. BECCS is thus conceivable at a limited scale, without changes in global biomass flows and, accordingly, with limited potential for carbon dioxide removal. At the gigaton scale, however, it is unlikely that BECCS could be implemented without redirecting global biomass

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flows with social and environmental consequences that are virtually certain to be deleterious in nature.

Direct air capture (DAC) is a third major type of NET which, at the time of writing, has become subject to a remarkable burst in commercial interest and, arguably, hype. DAC includes different methods for filtering out carbon dioxide from ambient air via large industrial units, allowing its subsequent storage but also utilization in construction materials or for producing synthetic fuels. In contrast to carbon capture at point sources (such as power stations), the concentration of carbon dioxide in ambient air is relatively low, translating into comparatively greater technical challenges and higher costs. While DAC has seen steady decreases in capture costs, its performance is nowhere near the level of carbon capture technology for point sources of carbon dioxide emissions. For the time being, the physical and technical limits to the economic efficiency of DAC remain unclear.[16] What is clear, though, is that any large-scale global deployment would require material and energy inputs of a magnitude that is challenging at best and crippling at worst.[17] Finally, large-scale DAC would require significant global infrastructural development, not just for capture facilities but also for the transportation and storage of carbon streams. Whether DAC is scalable to an extent that is consistent with annual carbon removals of somewhere between 3 and 12 Gt is very much an open question at present.[18] In principle, though, DAC could offer higher-quality carbon removals, in terms of permanence but also measurability and verifiability, than any other type of NET.

Given all of the various uncertainties and their possible negative side effects, the overall feasibility of NETs for large-scale carbon dioxide removal is very much an open question, which, in some way, makes it astounding that they occupy such a central place in the scientific and political debate.[19] As I will discuss, the lack of effective international instruments for facilitating their deployment at scale is similarly surprising.[20] Yet, while NETs are widely accepted as an essential element for achieving climate neutrality by the middle of this century, the second category of proposed climate engineering techniques is substantially more controversial. SG aims at the modification of planetary albedo: by reducing the imbalance between the solar energy which the planet absorbs and the energy which it reflects back into space, the greenhouse effect would be limited or eliminated.[21] The dominant current proposal for SG involves the injection of reflective particles into the stratosphere, creating an artificial cooling effect similar to the way that large volcanic eruptions do.[22] This would most likely take place via aerosol dispersion from high-altitude jets, although tethered balloons and even land-based artillery systems have been considered.[23] Marine cloud brightening is another suggestion, whereby specialized vessels spray vaporized seawater into the air, thus increasing cloud albedo.[24] High-altitude balloons have been discussed as another possibility,

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and one that would lie within the reach of civil society movements coordinating simultaneous global releases via social media.[25] Ship-wake brightening is a somewhat more extravagant proposal, whereby surfactants would be used to make the bright bubbles generated from ship propellers persist for several days. By retrofitting a sizeable share of the global shipping fleet with appropriate engine modifications, measurable changes in planetary albedo would occur.[26] By far the most spectacular proposal, and one that is commonly used to ridicule the notion of SG as such, are space-based reflectors, notably mirror-like structures deployed at the Lagrange point between Earth and the sun, but possibly also in the shape of reflective particle clouds. Finally, cirrus cloud thinning is a method often grouped within the category of SG. This method would not, however, increase reflectivity to redirect sunlight before warming up the planetary surface, but rather facilitate the escape of planetary heat into space by reducing the heat-trapping effect from high-altitude cirrus.

The artificial cooling which SG would induce is scientifically well understood and can even be observed in the aftermath of large volcano eruptions.[27] While it is virtually certain that SG would allow for significant leverage over global temperatures, the technology poses vast and possibly even existential risks. These are potentially exacerbated by the difficulty of terminating a running SG programme, as this would lead to global temperatures rapidly rebounding. The magnitude of this rebound effect would depend both on the speed of programme termination as well as on the amount of global warming which has, in the meantime, been suppressed. This so-called termination problem is one of many aspects that make the governance of SG problematic.[28] In addition, some types of SG might have adverse impacts on the ozone layer (leading to increases in harmful UV radiation), or global precipitation patterns (possibly implying droughts and harm to regional agricultural systems and global food security). SG also raises complex governance issues, such as the modality of political decision-making on global temperature targets or liability and redress for harmful regional side effects.[29] Against this background, calls for an international moratorium on the research and potential use of SG are getting louder.[30] At the same time, there appears to be growing scientific and political interest in developing and evaluating SG technology as a potential tool for global temperature control, particularly in the United States.[31]

The usefulness of 'climate engineering' as an umbrella term has increasingly been questioned in recent years. Both in the political and the scientific debate, NETs are increasingly being interpreted as distinct from, and unrelated to, SG. To some extent, this has enabled NETs to emerge as a core feature of mainstream climate policy while creating safe distance from the political controversies that surround SG. On the one hand, it is certainly true that the two categories operate in fundamentally different ways (atmospheric carbon removal versus albedo modification) and

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take effect over different timescales (decades versus possibly years, months, or weeks, depending on the type and intensity of SG intervention). On the other hand, an implicit assumption behind the disaggregation of climate engineering into two categories is that NETs are benign whereas SG poses unacceptable social, political, and environmental risks. Considering that in recent years NETs have seen a dramatic increase in political interest (offering governments a way to reduce their mitigation burden in the present by banking on large-scale removals in the future) as well as economic interest (particularly from entities in the cryptocurrency and blockchain domain banking on drastic future growth in carbon markets),[32] this is certainly a somewhat self-serving conclusion. For one, core risks associated with SG might be avoidable, as with ozone depletion from stratospheric aerosol injection or the occurrence of a termination shock.[33] Others, such as impacts on precipitation patterns, might well be less pronounced than typically assumed.[34] And while SG might be difficult or even 'impossible to govern fairly and effectively in the current international political system, under assumptions of effective global participation, inclusiveness, and justice',[35] the same holds for many other issue areas where flawed governance mechanisms might still produce outcomes that are superior to any politically feasible alternative. At the same time, the upswing in the political and commercial interests in NETs appears unhampered by the diverse and severe environmental and human impacts likely to result from large-scale biomass-based solutions (i.e. forestry, BECCS, or marine carbon sequestration). Equally, the adverse spin-off effects that could result from the material flows, energy consumption, and infrastructure development required for large-scale DAC appears to have had limited impact on the current commercial hype. The governance challenges for any type of NETs are not trivial either, as the well-documented history of international carbon markets as well as instruments for forest carbon conservation clearly demonstrates. With all of this in mind, it appears unhelpful to understand NETs and SG as distinct and unrelated issues based on their respective risk profiles and governance challenges alone. It also clouds the perspective on the larger picture: that, no matter the many differences that exist between these two categories, but also between the specific techniques inside each of them, they are all expressions of a novel political paradigm in which global environmental degradation is progressing at a rate that requires constant increases in the scale and intrusiveness of response measures.

The following two sections elaborate on the rationales for deploying climate engineering technology. Both NETs and SG may complement global decarbonization efforts, allowing the transition to climate neutrality to be slower than it would otherwise have to be. In addition, a specific rationale for the development of SG technology, but not NETs, is its potential role as a measure of last resort in case of a non-linear and catastrophic destabilization of the climate system. As before, in the

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sections that follow I address the political issues at stake as well as the responses and non-responses of the various institutions which are of relevance to the field, before turning to the broader conclusions.

5.1 Transitioning to Net Zero

The currently 193 parties to the 2015 Paris Agreement on Climate Change commit to '[h]olding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels'.[36] Reaching these targets requires climate neutrality by approximately mid-century, earlier for 1.5°C than for 2°C. 'Climate neutrality', or 'net-zero emissions', means reducing emissions as far as technically, economically, and politically feasible, and compensating for residual emissions sources by permanently removing carbon dioxide from the atmosphere through technical and natural processes. At the time of writing, most governments have adopted one or the other commitment to net zero, yet major differences exist in terms of targets time tables, and, crucially, whether net zero refers to *all* greenhouse gas emissions or whether it covers carbon dioxide only.[37]

Today, NETs are widely accepted as an indispensable element of the net-zero transition, including in the integrated assessment models that examine the long-term temperature implications of the complex interplay between social, economic, technological, natural, and other factors.[38] Not only can they potentially compensate for sectors where zero emissions are likely technically not feasible, such as shipping, aviation, and certain heavy industries; rather, even where technical feasibility exists, the transition towards zero emissions can impose costs of a political nature. NETs can reduce these costs by enabling transitions that are smooth and gradual rather than sudden and disruptive. By giving industry more time to adjust its business model, NETs would reduce the risk of political blowback.

Let us consider several recent scenarios. The International Renewable Energy Agency (IRENA) develops a 1.5°C scenario where, by 2050, carbon abatement reduces emissions by 36.9 $GtCO_2$ below 2018 levels.[39] By 2050, this requires approximately 5 $GtCO_2$ of annual removals via BECCS and 2 $GtCO_2$ of annual carbon capture at point sources. This is a lower-end scenario which, accordingly, has ambitious additional components, notably an 8 per cent reduction in total final energy consumption, with 30 per cent of global energy demand by 2050 being served from biomass as well as hydrogen, both 'green' (i.e. produced via renewable energy) and 'blue' (i.e. produced via fossil energy in combination with CCS). Sky, a 2°C scenario recently developed by Shell, constructs a net-zero world in the year 2070 with a larger residual role for fossil fuels (22 per cent of global energy consumption versus 10 per cent in the IRENA 2050 scenario), a later scale-up of

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hydrogen, and annual removals of 9.5 Gt via CCS and BECCS.[40] In the more recent Sky 1.5 scenario, geared towards a 1.5°C temperature target and taking into account the impacts of, and responses to, the COVID-19 crisis, the world reaches net-zero carbon dioxide emissions in the late 2050s and global net-negative emissions of annually ~10 $GtCO_2$ in the 2070s. This requires annual CCS, as well as carbon capture and utilization, of up to 12 $GtCO_2$. These values are not untypical. An IPCC analysis of various scenarios for 1.5°C or 2°C finds removals of up to 9.5 $GtCO_2$ per year via BECCS in 2050, and even 16.3 $GtCO_2$ by 2100. While some scenarios are towards the lower end, it is important once more to point out that even low-end BECCS deployment with annual removals of 3.3 $GtCO_2$ could require energy crop cultivation on up to half of the contemporary global cropland area.[41]

As the 2°C and especially the 1.5°C target require a systemic, global transformation which appears increasingly unlikely to unfold at the required speed and scale, the pathway to net zero may come to entail so-called overshoots, or temporary breaches of temperature targets.[42] Contemporary models increasingly assume that the insufficient speed and scale of the net-zero transition make some degree of overshoot unavoidable. The size of a potential overshoot in regards to either the 1.5°C or the 2°C target might be larger or smaller, yet ultimately implies temporary global warming at levels that are, by definition, unsafe. This is where SG might play a role: the temporary deployment of proposed techniques such as stratospheric aerosol injections, marine cloud brightening, and cirrus cloud thinning might 'shave the peak' of global warming, meaning that it would artificially reduce average surface temperatures during an overshoot period.[43] SG would thus mask the excess warming associated with an overshoot scenario and thereby fulfil a similar function to NETs – that is, allowing a softer transition towards net zero than would otherwise be possible. Despite this similarity, there are crucial differences. Most importantly, NETs address the underpinning cause of global warming, in the form of excessive atmospheric greenhouse gas concentrations, whereas SG does not. As SG influences only the planetary radiation budget and not greenhouse gas concentrations as such, there are aspects associated with global warming that it cannot remedy, notably the deleterious increase in ocean acidity levels which results from global carbon dioxide emissions. A second difference between NETs and SG is in their economics. For instance, a global programme for stratospheric aerosol injections at a scale sufficient for substantially reducing or even eliminating further global warming would have negligible costs compared to the costs of the net-zero transition, possibly no more than a few hundred million US$ per year.[44] This is in marked contrast to NETs, which will likely require annual investments that amount to a non-trivial percentage of global GDP.[45] And whereas scale-up is a central problem with NETs, a global SG programme could possibly be operational within years or even months. Third, NETs and SG differ in terms of their risk

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profiles. The frequent assumption that NETs are more benign than SG is, in all likelihood, wrong. As discussed earlier, NETs have potentially severe impacts on the global environment that, in aggregate, need not necessarily be lower than possible harm connected with SG. The difference is that SG is a wildcard technology with risks that are largely unknowable prior to full-scale deployment. Whereas the gradual scale-up of NETs over the course of decades would be accompanied by the systematic assessment of risks and environmental impacts, SG entails 'unknown unknowns' that might be impossible to anticipate. This lack of predictability also has important implications for the governance of SG, as unanticipated risks might lead some governments to reconsider their support for global SG deployment, leading to conflicts with other governments that remain committed to the programme nevertheless.

This brief discussion highlights several promises and perils of climate engineering. On the one hand, both NETs and SG offer high leverage for managing anthropogenic impacts on the global environment. On the other hand, they also threaten different types of harm and, in the case of NETs, may also lead to injustice through adverse impacts on the global land system that would principally affect the societies of the Global South. Yet there is another peril associated with climate engineering: the threat of crowding out feasible alternatives. The question of to what extent climate engineering delays, or even deters, comprehensive emissions reductions has received a great deal of attention in the scientific literature. A key argument against NETs is that contemporary policies assume that significant potential for carbon dioxide removal will be available in the future. Yet if NETs turn out not to work at scale, a breach of international temperature targets is virtually unavoidable.[46] In comparison, there is no doubt that SG would 'work' in the sense of keeping global warming in check, albeit at the price of unforeseeable and possibly systemic risks. However, considering that SG is cheap whereas mitigation is expensive, governments might reduce their commitments to mitigation due to the expectation that SG would offer a cheap way of shaving-off the resulting temperature overshoots.[47] The problem, accordingly, is not that NETs and SG simply allow mitigation to proceed more slowly than would otherwise need to be the case, thus granting a degree of political flexibility. The problem is rather that both, in similar ways, might weaken political commitments to rigorous mitigation and instead encourage slack in the expectation of technological unicorns providing an easy fix at some point further down the road. Together with the other perils discussed herein, there is reason to be sceptical about the prospects of either type of climate engineering. But then, there is also reason to be sceptical about the potential for conventional emissions control strategies to deliver a safe level of global temperature increase. The core question is perhaps less whether one is 'for' or 'against' one or the other type of climate engineering; rather, the desirability, or

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even necessity, of climate engineering hinges on how we estimate the comparative effectiveness of the available alternatives.

5.2 Responding to Catastrophic Climate Change

There is a specific relevance to SG, but not NETs, in the context of tipping points: thresholds in the climate system that, when breached, trigger non-linear responses with catastrophic impacts.[48] Tipping points are of a categorically different nature than climate impacts from slow onset processes that, over the course of decades, place increasing pressure on coastal zones through gradual sea-level rise, or that increasingly expose agricultural systems to hydrological stress, and so forth. Tipping points are events with unknown but non-trivial probabilities that could cause disastrous and irreversible impacts at the civilizational scale. Various tipping points have so far been identified. Cascading ice sheet collapse in Antarctica or Greenland could increase sea levels by several metres, flooding sizeable parts of global land area and making entire regions and nation states physically disappear. Methane releases, for instance from the permafrost in the polar regions or from hydrates in the deep sea, could increase with rising temperatures, becoming self-reinforcing and thus leading to rapid and drastic temperature increases. Very high levels of atmospheric carbon dioxide could disrupt the formation of stratocumulus clouds, which would reduce the reflectivity of the planet and thus lead to additional global warming worth several degrees Celsius.[49] A collapse of the Atlantic Meridional Overturning Circulation, which transports warm water from the Southern to the Northern Atlantic and cold water in the other direction, would lead to 'prominent cooling' in Europe and elsewhere in the North.[50] To make matters worse, the breach of one such tipping point could cause cascading effects that lead to additional breaches in other tipping points.[51]

Such non-linearities represent the fat-tail risks of climate change. Neither their probabilities nor their ultimate impacts can be determined with certainty. Where such events occur, though, they can no longer be managed by cutting greenhouse gas emissions, and their potential scale may well put them beyond the scope of pre-existing adaptation measures. Despite their existential dimensions, worst-case scenarios of catastrophic climate change draw somewhat limited scientific interest, possibly because of the methodological challenges which they entail. Possibly it is also because amplification and misrepresentation of ambiguities and uncertainties in the scientific record, by organizations acting on behalf of the fossil industry, has over decades biased the scientific discourse towards the avoidance of statements that might later be misconstrued as 'alarmist'.[52] If such scenarios would occur, however, SG, in particular stratospheric aerosol injections, may here constitute a measure of last resort,[53] allowing governments 'to slim down the bad fat tail of

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high temperatures quickly as an emergency response'.[54] The efficacy of an SG response to a climate emergency is not necessarily clear, though. For some types of tipping points – for instance, self-reinforcing methane releases – SG could well prevent or offset rapid increases in global temperatures, albeit without providing a remedy for the increased atmospheric greenhouse gas stocks. Other processes, such as cascading ice sheet collapses, would likely maintain themselves even if global cooling were suddenly introduced via SG. Thus, the idea of SG as a potential emergency measure does have *some* merit, especially in the absence of any sort of viable alternative. At the same time, it does not provide a universal remedy for every possible scenario of catastrophic global climate change.[55]

A different question is whether SG, if understood exclusively as such a measure of last resort, would exhibit the same risk of mitigation deterrence that is sometimes associated with SG in the context of peak-shaving (discussed earlier). The reason is that there are two different 'slippery slope'-type problems by which SG might reduce the ambitiousness of global mitigation efforts. The first one pertains to research: if SG technology is available, so the argument goes, governments will deploy it. The second type of slippery slope is the expansion of an ongoing SG programme beyond the scale at which it was initially intended: as marginal increases in SG intensity imply large economic cost reductions over the short term, governments would have incentives for overutilization – that is, deployment that goes beyond limited peak-shaving. This second type of crowding out of feasible alternatives would, accordingly, not apply to situations where SG capacities are strictly considered as an emergency backup plan with a regulatory firewall preventing their frivolous use as a complement for emissions mitigation. In those terms, SG as a measure of last resort is thus possibly somewhat more benign than SG in the context of peak-shaving.

5.3 The London Convention and the London Protocol

The 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (LC) and its 1996 protocol (LP) constitute central international instruments for the control of marine pollution. With narrow exceptions, the LC obliges parties to prohibit the dumping of particularly harmful substances listed in its Annex I; to require a prior special permit for the dumping of substances listed in Annex II; and to require a special general permit for all other substances. The LP, which supersedes the relevant provisions of the Convention, applies a stricter 'white-list' (or 'reverse list') approach, obliging its parties to prohibit the dumping of *all* types of matter *except* those listed in the protocol's Annex I and subject to a prior permitting process. The LP thus reflects the broad turn towards the precautionary principle in international environmental law in the wake of the 1992 Rio Earth Summit.

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Starting from the late 1990s, the LC/LP started responding to challenges associated with climate engineering, but also specifically with carbon capture and storage (CCS) as a precursor to large-scale NETs. The scientific and policy debate on CCS, in fact, predated the debate on NETs. Initially, the intention behind CCS technology was merely to clean the fossil energy supply. By installing cost-efficient filters in power stations, and by finding some way of permanently storing the capture carbon, CCS would unlock clean coal and clean natural gas – or, at the very least, allow for a smoother decarbonization of the power sector, an argument that later returned in the debate on NETs, as discussed previously. CCS, whether as an isolated component in coal- or natural-gas-fired power stations or in a more ambitious conjunction with bioenergy (BECCS), requires storage capacity. One particularly attractive choice is geological formations, including below the ocean floor, where injections of liquefied carbon possibly allow for safe, long-term storage.

Numerous complex regulatory issues attach to CCS and subsoil geological storage. During the 1990s, when optimism regarding the economic feasibility of CCS was still unbridled, various countries moved towards demonstration projects. A notable example is the Sleipner CCS facility, an offshore installation operated by the Norwegian state-owned enterprise Equinor (previously Statoil). However, the law of the sea was not favourable for CCS. Under the LP, in particular, the question arose of whether carbon dioxide legally constitutes 'waste or other matter' and whether its injection into subsoil geological formations amounts to 'dumping'. If the answer to both questions is yes, not only would carbon injections be prohibited for the contracting parties, but even the transboundary movement of carbon dioxide, where capture sites and storage sites are located in different jurisdictions, would be illegal.[56] The original provisions of the LP did not leave a lot of legal wiggle-room: the protocol defines dumping, inter alia, as 'any storage of wastes or other matter in the seabed and the subsoil thereof'.[57] The term 'wastes or other matter', in turn, broadly includes 'material and substance of any kind, form or description'.[58] As carbon dioxide streams were not initially listed in the Annex list of wastes or other matter, they were not eligible for exemption from the blanket prohibition on dumping, under the condition that appropriate measures for permitting and regulatory oversight would be in place. Finally, the LP obliged parties to ban exports of carbon dioxide streams destined for subsoil injection, irrespective of whether or not they were listed in Annex I.[59]

These two issues – injection and transboundary movement – were obviously linked: the dearth of suitable storage sites means that any deployment of CCS or BECCS at a non-trivial scale would require substantial volumes of carbon dioxide to be transported across international borders prior to injection. Curiously, the injection problem turned out to be easier to solve than the transportation problem. This has largely procedural reasons. In 2006, parties to the LP agreed to include

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carbon dioxide streams, given that these originate from capture processes and are intended for storage, in the Annex I list of substances that are eligible for a potential exemption from the dumping provision. Pursuant to LP Article 22, such Annex I amendments automatically enter into force without requiring additional ratification at the national level. In contrast, the prohibition of exporting carbon dioxide streams intended for subsoil injection under LP Article 6 required an amendment of the protocol itself. This, in accordance with Article 21 and other provisions of international law such as Article 40 of the 1969 Vienna Convention on the Law of Treaties (VCLT), required ratification by two-thirds of the LP's contracting parties before entering into force. The 2009 amendment of Article 6, whereby 'the export of carbon dioxide streams for disposal in accordance with annex 1 may occur', subject to the existence of an appropriate regulatory framework, has not entered into force at the time of writing due to an insufficient number of ratifications. To ameliorate this problem, parties have in the meantime decided on the provisional application of the amendment barring its eventual entry into force.[60] Taking into additional consideration that the VCLT generally requires states 'to refrain from acts which would defeat the object and purpose' of amendments and other forms of international agreements,[61] the Article 6 amendment possesses *some* normative force under international law despite its ratification deficit.

In addition to the removal of crucial regulatory barriers to CCS deployment in a transboundary context, the Scientific Group which advises parties to the LC/LP developed two sets of guidelines intended to inform the design and implementation of CCS projects: the 2006 Risk Assessment and Management Framework for CO_2 Sequestration in Sub-Seabed Geological Structures and the 2007 Specific Guidelines for the Assessment of Carbon Dioxide for Disposal into Sub-Seabed Geological Formations.[62] Together, these put in place a dedicated permitting regime for subsoil CCS while also allowing a better characterization and management of associated risks.

Aside from subsoil carbon storage, being a crucial precursor technology for certain types of NETs, the LC/LP also started responding to broader issues of marine climate engineering during the 2000s, including in the context of the Haida Gwaii incident. The islands of Haida Gwaii are located in the Northern Pacific off the Canadian coast. In 2012, the Haida Salmon Restoration Company conducted a controversial (and illegal) experiment in ocean fertilization: in order to increase local salmon stocks, the Canadian company dumped 120 tonnes of iron fertilizer into the sea in order to enhance the growth of phytoplankton.[63] The resulting phytoplankton bloom covered an ocean area of more than 30,000 km^2, leading to increases in local salmon stocks while also widely being seen as a breach of international environmental law. While this was the first time that ocean iron fertilization was used in a commercial context, scientific experiments of this sort

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had already commenced in the 1990s. As a nutrient, iron is a limiting factor on ocean primary productivity in many regions of the globe. Its deliberate introduction of iron into the marine environment stimulates photosynthesis and thus enhances the sequestration of carbon dioxide in marine biomass. Already three years prior to Haida Gwaii, iron fertilization in the Southern Pacific during the German–Indian LOHAFEX experiment stirred intense controversy among environmentalists. This was only the latest in a series of experiments going back to the initial IronEx II project, which had fertilized a region in the Eastern Pacific, with mixed results, in 1995.[64] Projects such as these have to tread a tightrope: on the one hand, marine scientific research falls within the scope of the freedom of the seas as one of the foundational norms of the international law of the sea.[65] On the other hand, they have the capacity to cause harm to the marine environment which would bring them into conflict with existing international norms and rules dealing with the protection of that environment. Things are more clear-cut for commercial operators that cannot credibly claim to act within the scope of legitimate scientific research. This was the case for the 2012 dumping scheme of the Haida Salmon Restoration Company. That company was run by the same businessman who, five years earlier, had made a bid for a fertilization scheme close to the Galapagos Islands with an entity called Planktos Corporation. This Galapagos project had ultimately failed to secure adequate funding due to what Planktos referred to as a 'highly effective disinformation campaign' by its detractors, presumably including activists concerned with the potential environmental impacts.[66] Five years later, Haida Gwaii was the first actual instance of ocean fertilization for commercial reasons. The Haida Salmon Restoration Company allegedly received US$ 2.5 million from an indigenous community looking to replenish local fish stocks. Among the somewhat mysterious details of the case, it also appears that the company promised to repay this money through the carbon credits which the scheme would supposedly generate.[67] While many details of the case cannot readily be verified, this would have presumed that some carbon offsetting mechanism or emissions trading system would have recognized ocean iron fertilization as a creditable activity. This is simply not the case: neither today nor in the past would it be possible to obtain tradable carbon credits for activities that are as spectacularly unsound as ocean iron fertilization.

Regardless of the motives and the logic behind these commercial fertilization schemes, governments and environmental groups latched onto the potential environmental risks early on. In 2007, the scientific groups of the LC and LP 'noted with concern the potential for large-scale ocean iron fertilization to have negative impacts on the marine environment and human health',[68] a position which the contracting parties to the LC/LP echoed later that year (as did the contracting parties to the CBD in 2008, as I will discuss). From a legal perspective, ocean

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iron fertilization is more complex than it might seem. UNCLOS broadly requires states to 'prevent, reduce and control' pollution of the marine environment, including from dumping, namely 'any deliberate disposal of wastes or other matter' and 'any deliberate disposal of vessels, aircraft, platforms or other man-made structures'.[69] These definitions are mirrored by the LC and the LP. All three agreements, however, specify as an exemption from that definition 'placement of matter for a purpose other than the mere disposal thereof', given that such placement does not run counter to the aims of either agreement.[70] Depending on perspective, ocean iron fertilization might fall under this exemption, considering that its purpose is not 'merely' disposal, or not even disposal at all. The uncertainties and risks which it entails, however, can be construed as inconsistent with the overarching aim of protecting the marine environment at the core of the LC/LP (and, of course, UNCLOS and a wide range of other agreements in international environmental law as well as the law of the sea). Technically, this means that any 'placement of matter for a purpose other than the mere disposal thereof' would still constitute dumping if it runs counter to the goals of the LC/LP. The implications differ between the two agreements Under the LC, fertilization activities that involve the dumping of iron or other substances, except for those which are listed in Annex I and thus subject to a categorical prohibition, would be permitted under a prior special permit or prior general permit, granted by the relevant contracting party. Under the LP, fertilization would only be permissible for substances within the scope of the protocol's Annex I exemptions from its blanket prohibition of dumping. Practically, this means that the fertilizer would need to be classified as 'inert, inorganic geologic material' or as 'organic material of natural origin'.[71]

Starting in the 2000s, these legal issues caused political concerns regarding the capacity of the international dumping regime for regulating ocean fertilization in an effective and environmentally sound manner. With the status of ocean iron fertilization under the LC/LP being ambiguous, one issue was the applicability of existing definitions and operational provisions. A second, related issue was how to adjust the regulatory frameworks of the LC and the LP to accommodate the environmental and regulatory challenges brought about by the intensification of ocean fertilization activities. Few (if any) governments supported the idea of ocean fertilization for large-scale carbon sequestration or other purposes such as fish stock restoration. However, various governments, particularly those of developed countries, were concerned about possible regulatory overreach that would infringe on the freedom of marine scientific research as a core normative element of the law of the sea.[72]

In 2008, the contracting parties cleared the legal fog, deciding that ocean fertilization activities, defined as 'any activity undertaken by humans with the principal intention of stimulating primary productivity in the oceans', fall

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unambiguously within the scope of the LC and the LP. Further, legitimate types of research that involve ocean fertilization would be understood as 'placement of matter for a purpose other than the mere disposal thereof', as discussed earlier. To the extent that such research activities do not contravene the overarching goal of protecting the marine environment under the LC/LP, they would accordingly not constitute 'dumping'.[73] Thus, while parties universally opposed frivolous fertilization activities with dubious motives, the trickier issue thus amounted to the regulation and definition of legitimate scientific research activities. Legally, and in line with this, this revolved around two separate questions: first, under which conditions should a proposed fertilization scheme be considered as 'legitimate scientific research' and thus be understood not as dumping but rather as 'placement of matter for a purpose other than the mere disposal thereof'? And, second, under which conditions should proposed activities that amount to such 'placement' be considered as not contravening the overarching goals of the LC and the LP, and accordingly not be understood as dumping? These two issues are at the core of the Assessment Framework for Scientific Research Involving Ocean Fertilization, which the parties to the LC adopted in 2010. The Assessment Framework contains specific criteria that define whether or not a proposed activity is sufficiently scientific in character, including that 'economic interests should not influence the design, conduct and/or outcomes of the proposed activity' and that '[t]here should not be any financial and/or economic gain arising directly from the experiment or its outcomes'.[74] For a proposed activity to be determined as properly scientific, the framework provides criteria for the environmental assessments, including for risk assessment, on the basis of which the relevant governments then decide whether or not the activity contravenes the goals of the LC.

In parallel to these developments on ocean iron fertilization, parties to the LP began exploring regulatory implications and options for marine climate engineering more broadly. Beyond fertilization schemes, there are various other proposed techniques for climate engineering that, in one way or another, have implications for the marine environment. These are not necessarily relevant from the perspective of ocean dumping. Marine cloud brightening, for instance, is arguably the second most discussed idea from the portfolio of SG, behind stratospheric aerosol injections, although its implications for the law of the sea are likely beyond the ambit of the LC/LP. However, against the background of rapid developments in technology and technological proposals with regulatory implications that can require significant time to understand and build political consensus around, parties understood ocean iron fertilization as a component of the broader suite of proposed climate engineering techniques of potential relevance for the LC/LP, albeit a component in need of regulatory priority action.

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In 2013, contracting parties adopted a formal amendment to the LP. As with the Article 6 amendment on exports of carbon dioxide streams discussed earlier, this amendment has not entered into force at the time of writing. If and when it does, it would amend LP Article 1 to define marine climate engineering as 'a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects'.[75] It would also add a new article prohibiting marine climate engineering techniques listed in the new Annex 4, unless these listings would specify criteria under which exceptions might be granted. Such exceptions would require the relevant parties to grant permits in accordance with the specification of the new Annex 5, as well as any specific guidelines adopted by the contracting parties. Annex 4 presently lists only ocean fertilization, which may only be permitted subject to 'any specific placement assessment framework', thus indirectly referring to the LC's Assessment Framework discussed earlier. In 2022, the correspondence group on marine geoengineering decided to consider four additional schemes for potential listing in Annex 4: ocean alkalinization, biomass-based carbon sequestration, measures to enhance ocean surface reflectivity, and marine cloud brightening.

The amendment would also exclude all marine climate engineering activities listed in Annex 4 from the scope of LP Article 4, which entails both the protocol's blanket prohibition of dumping as well as the possibility of granting permits for the dumping of substances other than those listed in Annex 1, subject to the provisions of Annex 2. As a consequence, any permitting procedures for marine climate engineering techniques are governed by the specific provisions under the new Annex 5 while making the general provisions under Annex 2 inapplicable. To some extent, this would create a sub-regime for marine climate engineering that is somewhat disconnected from the other parts of the LP that address dumping at a more general level. As with the amendment on the export of carbon dioxide streams, Article 18 of the VCLT applies while the entry into force is pending. Those parties to the LP that have accepted the amendment are accordingly obliged 'to refrain from acts which would defeat the object and purpose' of that amendment.[76] Practically, this would prevent parties from authorizing Annex 4 activities without deferring to its criteria that specify the conditions under which authorization may be considered, as well as to the provisions of Annex 2 and any applicable additional and specific guidance which parties may have adopted previously. To put it differently: the provisional application of the marine climate engineering amendment of the LP appears to be the only way in which the parties that have consented to that amendment could act in a manner that does not run counter to the amendment's 'object and purpose'. The implications of this general requirement under the VCLT likely have greater practical consequences than is the case for the

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amendment on the export of carbon dioxide streams. There, parties that have consented to the amendment are merely required *not* to prohibit any export of relevant carbon dioxide streams. For the amendment on marine climate engineering, any decision to authorize Annex 4 activities that is not based on assessment criteria which are identical (or at least substantively similar) to those which the amendment contains would likely defeat both its object and purpose. In the former case, the rules of the VCLT imply an obligation not to prohibit. In the latter, they imply an obligation to take regulatory decisions based on a systematic assessment of whether a proposed marine climate engineering activity is sufficiently scientific and whether it is compatible with the goals of the LP.

The preceding discussion shows that the LC/LP responded to the emerging challenges of subsoil carbon storage and marine climate engineering in ways that were comparatively both swift and deep, entailing formal treaty amendments that tend to be rare due to their associated political costs. At an abstract level, this is perhaps because neither subsoil carbon storage nor marine climate engineering in general, and ocean iron fertilization in particular, created significant problems for the respective institutional responses. In terms of state interest, neither issue entailed a meaningful split between proponents and detractors. For sure, some states might have opposed subsoil carbon storage on the grounds that, being a component of some types of CCS and NETs, it deters mitigation. Others might disagree with the need to carve out regulatory exceptions for marine scientific research involving ocean iron fertilization or other types of marine climate engineering. Yet neither of these issues appears to have immediate and substantial distributive implications. For transboundary movements of carbon dioxide streams, a permissive regulatory approach does not entail obvious drawbacks for states concerned about mitigation deterrence, keeping in mind that the presently insufficient viability of CCS appears to hinge more on the 'capture' than the 'storage' side, and that export bans are irrelevant where capture and storage sites are located in the same jurisdiction and cross-border transportation is unnecessary. For marine climate engineering, scientific research exemptions may raise similar concerns regarding mitigation deterrence. Yet such concerns are likely to be assuaged by the virtually universal international opposition to ocean iron fertilization and similar schemes as a method for large-scale carbon sequestration. The broad agreement among governments (and other stakeholders) to consider such types of intervention into marine environments as undesirable instances of dumping very likely supersedes abstract considerations regarding possible slippery slopes of contemporary research that might end up having a deterring effect on mitigation in the future. Without disregarding or trivializing the political challenges that characterize many instances of institutional bargaining in a similar manner as the LC/LP, disagreements between governments can exist at different levels, with some

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of these levels having more problematic implications for international cooperation than others. With the LC/LP coming to de facto prohibit the commercial use of Annex 4 climate engineering methods, this effectively closes the door on large-scale ocean iron fertilization as a NET.[77]

5.4 The OSPAR Convention

The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR convention) is one of the rare cases in international law where an international treaty results from the fusion of two previously separate ones: in this case, the 1972 Oslo Convention regulating ocean dumping and the 1974 Paris Convention on marine pollution from land-based sources. Starting in the early 2000s, the parties to OSPAR confronted a similar dilemma as the parties to the LP: how to reconcile subsoil carbon storage as a potentially important element of climate policy with obligations related to the protection of the marine environment? Aside from its general obligation on parties to aim at the prevention and elimination of marine pollution in the convention area and to attempt to protect it from adverse anthropogenic impacts more broadly,[78] OSPAR uses a reverse-list approach similar to the LP. It defines dumping as the 'deliberate disposal … of wastes or other matter' and excludes from that definition 'placement of matter for a purpose other than the mere disposal thereof, provided that . . . it is in accordance with the relevant provisions of the Convention'.[79] With carbon dioxide streams initially not being listed among the substances which states may consider for an exemption from the overall prohibition on dumping, OSPAR posed a similar regulatory hurdle for subsoil injections as the LP without, however, containing any provisions that would impede transboundary movements from capture to storage sites.

The response under OSPAR involved four elements. First, OSPAR's guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations provides guidance for ensuring permanent and safe storage while preventing harmful environmental impacts if and when carbon leakage should occur. Second, parties amended OSPAR Annexes 2 and 3, respectively, containing the convention's operational provisions on dumping and waste incineration, as well as pollution from offshore sources for which, different from the LP, it contains a separate set of rules. The amended Annex 2 allows parties to permit the dumping of carbon dioxide streams into subsoil geological formations, given that these are intended for permanent storage, do not cause significant adverse impacts, and do not contain additional substances for disposal. The amended Annex 3 exempts such carbon dioxide streams from the general prohibition on dumping from offshore sources, such as the previously mentioned Sleipner facility (which is located inside the convention area).[80] Third, in a decision on the storage of carbon dioxide streams

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in geological formations, parties provide an overarching framework containing definitions and procedural rules related to permitting and reporting. Fourth, and finally, parties issued a decision prohibiting carbon storage on the sea bed and in the water column.[81] Minor nuances notwithstanding, responses under OSPAR thus largely mirror the developments on subsoil carbon storage under the LP described earlier.

5.5 The Convention on Biological Diversity

As already noted, the CBD, in time, became somewhat of a central forum for the international governance of the environment–technology interface. In some sense, this is by design. As I discussed in Chapter 4, the CBD emerged from a compromise between governments of (largely developed) countries aiming for better environmental protection and governments of (largely developing) countries that attempted both to carve out space for socio-economic development and to ensure adequate participation in the supposed gold rush of the biotechnological revolution of the 1980s. The former resulted in the CBD's objective of the sustainable use of biodiversity, the latter in the objective of fair and equitable benefit-sharing in regards to the (biotechnological) utilization of genetic resources. The CBD thus had a significant technological component from the outset. This, together with the vast range of conceptual and causal linkages between 'biodiversity' and practically any conceivable technological field, possibly facilitated the CBD's transition into a centrepiece of global technology governance, albeit one that is regularly accused of overreach and anti-technology bias. Attempts by governments to keep certain controversial issues off the agenda of institutions which they consider as particularly important may also have facilitated the aggregation of these issues within the CBD. Governments may have been unwilling to enter into controversial discussions on climate engineering, and SG in particular, within the FCCC, instead being content with outsourcing the issue to the CBD, where public attention is lower and tangible outcomes are (even more) unlikely. Besides the political games, it is clear that some proposed climate engineering techniques would have crucial implications for biodiversity in the context of the CBD's objectives. For some such techniques, these implications might be rather indirect – for instance, the possible alterations to global precipitation patterns that could result from some SG schemes. Some techniques, such as DAC, might turn out to be completely unrelated to the CBD and its objectives. Yet others would have rather immediate and obvious impacts. This includes all types of NETs that involve changes to the global land system, including BECCS but also large-scale forestry-based measures. It also includes certain types of marine climate engineering, such as fertilization schemes that impact marine biodiversity through its effects on the primary productivity of

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oceans, or ocean liming for enhancing marine carbon sequestration by reducing acidity.

In marked contrast to the LC/LP, responses to climate engineering under the CBD have been limited to regulatory adjustments lacking in specificity as well as legal bindingness. As mentioned in Section 5.4, the contracting parties to the CBD followed the lead of the LC/LP and, in 2008, emphasized the importance of precautionary decision-making regarding ocean iron fertilization, as part of a broader decision on the linkages between biodiversity and climate change.[82] In 2010, parties adopted a consequential and controversial decision of significantly greater breadth and depth. Both the status and the precise meaning of this decision have been discussed at great length, and with great contention, in politics as well as in science.[83] Formally, that decision 'invites' parties to give qualified consideration to certain guidance related to climate engineering, namely the proposition that they might consider to '[e]nsure, . . . in the absence of science based, global, transparent and effective control and regulatory mechanisms for geo-engineering, . . . that no climate-related geo-engineering activities that may affect biodiversity take place'.[84] Stylistic questions aside, this definition is open to a wide range of possible interpretations, including quite a few that are mutually exclusive.

With these issues in mind, we may also take a step back and consider that the legal implications of this and similar decisions taken by the governing bodies of international institutions are a matter of dispute among international lawyers. They are generally understood to carry *some* normative force, although scholars disagree regarding their exact legal status. Together with the use of qualifying language in a manner that seems excessive even by the usual standards of international law, it is rather surprising that some civil society organizations chose, and continue to choose, to refer to this decision as a 'moratorium' or 'quasi-moratorium'.[85] As such, the decision does no more than encourage parties to the CBD to consider as fairly general guidance propositions that are widely understood and accepted as general, foundational components of international environmental law. In other words, it does not add anything of substance to what existing international agreements, customs, or legal principles imply for climate engineering, whether or not it entails potential consequences for biodiversity.

Perhaps the most interesting element of the CBD's decision is its self-limitation to instances where alternative, meaning 'science based, global, transparent and effective control and regulatory mechanisms' are absent.[86] Although every single component of this provision raises definitional questions, there is a broader issue at stake: in arguably most domains of global governance, there is substantial lag between the emergence of regulatory challenges and their resolution. In some cases, this lag might be longer and have implications of greater severity, possibly including the case of climate engineering. The CBD's decision accordingly amounts to

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a 'default' type of governance, lacking specificity and depth as a result of governments being unable to resolve fundamental normative disputes in the present, while offering an interim solution until the adoption of precise and binding rules becomes feasible in the future.[87] To put it differently, the decision does not offer an effective response to the regulatory challenge of climate engineering, but it emphasizes the relevance and applicability of existing, relevant elements of international law while also stressing the need for a dedicated governance mechanism. Yet, as indicated at the beginning of this section, the CBD's 2008 and 2010 decisions on climate engineering, just as its subsequent decisions that amount to little more than reiterations, are in stark contrast to the institutional responses under the LC/LP that I discussed previously. This raises the question of why the response to climate engineering under the CBD is characterized by ambiguity and a lack of legal depth, whereas the response to *marine* climate engineering, under the LC/LP, entails substantial sophistication in regulatory detail as well as significant ambition in terms of legal bindingness. I return to this question in the conclusions of this chapter. What is also of note, finally, is that parties to the CBD have consistently acknowledged the LC/LP as the primary international forum dealing with ocean fertilization, starting in 2008.[88] This phenomenon, where the boundaries of institutional jurisdiction are demarcated in order to ensure a smooth inter-institutional division of labour, can be observed in other issue areas as well.[89]

5.6 The Paris Climate Agreement

The Paris Agreement requires little introduction, being one of the most significant developments in the recent history of global governance as well as a milestone for climate policy. Adopted in December 2015 in the context of the UN Framework Convention on Climate Change (FCCC), the Paris Agreement operates through a peculiar mix of elements with different degrees of legal bindingness, at its core revolving around the nationally determined contributions (NDCs) which parties unilaterally put forth and that are subject to regular multilateral review, as well as a 'ratchet mechanism' whereby the ambitiousness of political commitments is intended to increase over time.[90] The agreement is notably the first climate treaty to adopt a target of 1.5°C global warming as an obligation of conduct, with parties accordingly being required to make good-faith efforts to collectively achieve that target. As a more stringent obligation of outcome, the Paris Agreement further requires them to limit average increases in surface temperature to 'well below' 2°C from the pre-industrial era to the end of the twenty-first century.[91] The agreement also specifies a general pathway for the implementation of these temperature targets, committing parties 'to reach global peaking of greenhouse gas emissions as soon as possible … and to undertake rapid reductions thereafter … so as to

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achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century'.[92] This is in line with the broad scientific and political consensus on the need to achieve climate neutrality around mid-century. At the same time, through its notion of balancing sources and sinks, the Paris Agreement grants an elevated role for NETs that is in marked contrast to the Kyoto Protocol, the centrepiece of international climate policy in pre-Paris period. The Kyoto Protocol contained among its core obligations the 'protection and enhancement' of greenhouse gas sinks and reservoirs, specifically within the context of forestry.[93] Forest carbon also played a limited role under the Kyoto Protocol's Clean Development Mechanism, where projects related to afforestation and reforestation could lead to certified emission reductions that parties would draw on for complying with their respective emissions targets under the protocol.[94] Over the lifespan of the Kyoto Protocol, forest-based carbon offsets, both under the Clean Development Mechanism and in other contexts, came under increasing scrutiny regarding the permanence of their carbon removals, their additionality, as well as other environmental and social issues. These reasons continue to dampen the political appetite for large-scale, forest-based measures in the Paris era. The central normative role of 'net zero' emissions under the Paris Agreement thus needs to be understood in the context of the wider discussion on NETs, which only partially overlaps with the more narrow issue of forest carbon. Regardless of whether we understand forestry as a type of NET on similar footing with BECCS or DAC, forests and other carbon sinks that previously mattered only in terms of compliance with national Kyoto targets came to be understood as a defining element of global emissions pathways and indispensable for achieving the international temperature targets of the Paris Agreement. To take matters even further, the removal of atmospheric carbon dioxide via NETs can be conceived of as a form of 'mitigation' in the same sense that the reduction of greenhouse gas emissions amounts to 'mitigation'. From this perspective, diverse procedural and substantive obligations related to mitigation, under both the Paris Agreement and the FCCC, would extend to NETs. This includes a variety of reporting requirements but also the obligation to 'pursue domestic mitigation measures' to implement the targets that parties have defined under their NDCs.[95]

As noted previously, in light of their centrality for climate policy, there is a surprising lack of policy support for NETs. This also extends to the Paris Agreement which, aside from its abstract conceptualization of NETs as a central element of international climate policy, neither provides operational incentives nor mobilizes financial or other resources that would support research, development, or deployment. This leads some observers to conclude that 'international climate policy may have to undergo a paradigm shift . . . in order to overcome the present chasm between the abstract notion of CDR [carbon dioxide removal] as relevant for

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Paris-aligned net-zero emissions targets and the widespread lack of operationalization in policy'.[96] Some observers consider Article 6 a potential overarching framework for governing NETs within the context of the Paris Agreement.[97] Drafted in a deliberately ambiguous manner to bridge political disagreement, Article 6 addresses voluntary cooperation between parties in order to achieve the emissions targets they have set out in their NDCs. It enables bilateral cooperation for 'the use of internationally transferred mitigation outcomes towards nationally determined contributions',[98] and, under Article 6.4, establishes a multilateral mechanism that is sometimes referred to as the 'Sustainable Mitigation Mechanism'[99] or 'Sustainable Development Mechanism'.[100] The latter is similar to the Kyoto Protocol's Clean Development Mechanism, meaning that it allows parties to credit emissions reductions from domestic mitigation actions towards the NDCs of other parties, subject to international oversight. The rulebook for the Sustainable Development Mechanism offers improvements over the Clean Development Mechanism, notably through stricter provisions for the avoidance of double-counting. The rulebook specifies that the Sustainable Development Mechanism covers activities related to the 'mitigation of [greenhouse gas] emissions that is additional,including reducing emissions, increasing removals and mitigation co-benefits of adaptation actions and/or economic diversification plans'.[101] While this brings NETs within the scope of activities that may, in principle, take place within the context of the Sustainable Development Mechanism, the rulebook mandates further discussions on associated issues of monitoring, reporting, accounting, permanence of removals, and avoidance of leakages.[102] At the November 2022 climate change conference in Sharm El-Sheikh, the Supervisory Body for Article 6.4 tabled a set of 'recommendations on guidance' for NETs,[103] with parties raising concerns regarding the 'absence of safeguards and provisions for reversals, and lack of differentiation between different removal types'.[104] The ultimate relevance of the Sustainable Development Mechanism for NETs will depend on which specific *types* will be considered eligible. Bearing in mind that the Sustainable Development Mechanism is intended not just to contribute to mitigation but also to support sustainable development, the extent to which NETs with intrusive environmental effects, such as BECCS and ocean-based methods, would fit into its scope is somewhat unclear. Direct air capture has arguably better prospects for aligning with the aims of the Sustainable Development Mechanism and poses substantially lower difficulties for the proper accounting of carbon dioxide removals than other types of NETs. Given that NETs will be significantly more expensive than conventional types of mitigation and removals, at least initially, it is crucial that the Sustainable Development Mechanism allows for financial transfers above market rates.[105]

Complications might result if the conceptualization of NETs under the Paris Agreement were to collide with the restrictive approaches developed under other

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international institutions. As noted earlier, the new provisions on marine climate engineering under the LC/LP effectively exclude large-scale ocean iron fertilization due to its inevitably 'commercial' – as in 'non-scientific' – character. Notwithstanding the contemporary political disregard for fertilization activities in the context of climate policy, at a more abstract level the permissive approach to NETs under the Paris Agreement is inconsistent with the restrictive approach to ocean iron fertilization, as one specific type of NET, under the LC/LP. Moreover, and semantics notwithstanding, NETs can amount to 'geoengineering' for the purposes of the relevant decisions developed under the CBD. This raises the question of how any potential collisions between the permissive and the restrictive governance approach would be resolved.

5.7 The United Nations Environment Assembly

In March 2019, Switzerland proposed a resolution to the United Nations Environment Assembly on 'geoengineering and its governance'. The draft resolution requested that the United Nations Environment Programme conduct a comprehensive assessment of climate engineering techniques (both NETs and SG) for informing further political debate. This assessment would have included the state of science, research, and development, as well as an analysis of contemporary governance frameworks and possible future governance options. While already limited in ambition, the Swiss proposal failed to garner sufficient political support, with major actors that include the United States and the EU considering the United Nations Environment Assembly an inappropriate forum for the matter.[106] The chief reason behind this disagreement was how the Swiss proposal grouped together NETs and SG, expressing concern about their 'potential global risks and adverse impacts' and noting 'multilateral control and oversight'.[107] This lack of differentiation led to opposition from states wary of potential international restrictions on NETs (and thus potential interference with national emissions targets).[108] I previously argued that the differentiation of 'climate engineering' into 'NETs' and 'SG' as distinct and largely unrelated categories is less intuitive than it may appear. However, what is also clear is that, in the political and academic discussion, this differentiation has become the dominant issue framing in recent years. The Swiss initiative was accordingly out of sync with the evolving debate. In any case, the hypothetical relevance and impact of an international assessment along the lines proposed by Switzerland would likely have not been in its substantive novelty. It is not entirely clear how such an assessment might have provided new insights that go beyond the abundant studies previously published on this subject, which already show a non-trivial degree of redundancy.[109] Instead, the significance of this assessment would have been an assertion of political authority for the multilateral

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governance of climate engineering under the auspices of the United Nations, as well as the re-linking of NETs and SG.

5.8 The Montreal Protocol and the Vienna Convention

The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer to the 1985 Vienna Convention for the Protection of the Ozone Layer was a response to rising global emissions of ozone-depleting substances, causing harmful increases in ultraviolet radiation to the surface of the planet.[110] It is widely recognized as *the* most effective international environmental agreement in history.[111] The Protocol aims at phasing out the production and consumption of dozens of ozone-depleting substances according to different timelines, with further differentiation between industrialized and developing countries. It provides technical and financial assistance to its developing country members through its Multilateral Fund and possesses robust procedures for addressing instances of non-compliance. The Protocol has evolved significantly over time, notably with its 2016 Kigali Amendment that aims at a global phase-out of emissions of hydrofluorocarbons, a class of substances that cause only marginal ozone depletion but are powerful greenhouse gases.[112]

The Montreal Protocol is potentially relevant to SG techniques that cause adverse impacts on the ozone layer. This notably includes stratospheric injections of SO_2, perhaps the most popular (and most notorious) proposal in the scientific discussion. The potential interface between SG and the Montreal Protocol has been noted going back to at least 2006.[113] However, the substantive provisions of the Protocol do not apply to ozone-depleting types of SG by default. Rather, its parties would need to take a formal decision to bring the relevant aerosols within the Protocol's ambit.[114] Yet even if this were the case, it is important to note that the Protocol does not directly regulate *emissions* of controlled substances, but rather their production, consumption, and trade. Accordingly, the hypothetical inclusion of SO_2 or analogous substances would create regulatory constraints 'only to the extent that the restrictions imposed on production or import of these substances would affect the actual carrying out of the activity'.[115] Despite its intuitive relevance for SG techniques that might harm the ozone layer, the Montreal Protocol accordingly has only a limited capacity for providing effective international regulation, barring major changes in its legal structure.

Aside from the Protocol itself, the overarching Vienna Convention requires parties to 'take appropriate measures . . . to protect human health and the environment against adverse effects resulting or likely to result from human activities which modify or are likely to modify the ozone layer'.[116] The focus on 'human activities' in principle gives this provision an extremely broad scope. However, this

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would require stratospheric injections of SO_2 or analogous substances to cause harmful impacts on human health or the environment that meet the criterion of 'adverse effects', which the Convention defines as 'changes in the physical environment or biota, including changes in climate, which have significant deleterious effects on human health or on the composition, resilience and productivity of natural and managed ecosystems, or on materials useful to mankind'.[117] Meeting this criterion could be legally demanding and, in any case, would not imply specific and substantial control obligations.[118]

Notwithstanding the legal challenges of regulating relevant types of aerosol-based SG under the Montreal Protocol and the Vienna Convention, parties have taken steps towards a more rigorous assessment of the SG–ozone linkage. The 2018 Scientific Assessment of Ozone Depletion, developed within the framework of the Montreal/Vienna regime and supported by the United Nations Environment Programme and the World Meteorological Organization, analysed the impacts of aerosol-based SG on the ozone layer and noted the complex potential effects on atmospheric chemistry.[119] In parallel, at the 30th Meeting of the Parties to the Montreal Protocol, some developing countries proposed a decision that, inter alia, would have requested the Protocol's Scientific Assessment Panel to produce further analyses of the linkages between SG and ozone depletion, including the role of potential 'unreported' deployment of SG, presumably referring to unilateral and covert use by a state- or non-state actor.[120] The proposal, with the exception of this latter aspect, subsequently garnered broad political support, including from Australia, Brazil, Canada, the EU, the United States, New Zealand, and Switzerland. This led to a decision to include the SG–ozone linkage in the quadrennial report of the Protocol's Scientific Assessment Panel, which was published in October 2022 and dedicates an entire chapter to the analysis of the potential impacts of stratospheric aerosol injections on the ozone layer.[121]

Overall, the responses under the Montreal Protocol and Vienna Convention to relevant types of SG have been severely limited so far. This is a curious outcome, considering that stratospheric SO_2 injections are widely understood as a technique with an extraordinarily large degree of technical and economic feasibility within a panoply of proposed SG techniques that includes a sizeable number of methods that are either extravagant (e.g. refreezing the polar caps to enhance planetary albedo) or fantastic (e.g. mirrors or reflective particle clouds in space). With ozone depletion constituting one of the major risks associated with stratospheric SO_2 injections, the international ozone regime is accordingly an obvious and intuitive forum for providing international regulation. Its specific institutional design, however, being focused on production, consumption, and trade, but not emissions, severely limits its overall regulatory impact. At the same time, the Montreal Protocol has demonstrated extraordinary adaptability throughout its

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history, which may well lead to future institutional outcomes that cannot readily be extrapolated from the present.

5.9 Conclusions

Climate engineering techniques, within the categories of both NETs and SG, promise different degrees of leverage for addressing the causes of global warming or for masking its consequences. For some types, particularly NETs, this leverage is smaller, considering that the significant resource commitments which BECCS or DAC require are well in excess of the costs associated with conventional measures for emissions mitigation at an equivalent level. Whereas large-scale forest-based measures would likely be significantly cheaper, possible limitations in their global sequestration potential might imply no more than a complementary role as part of a broader portfolio for carbon removal. In the case of SG, the comparatively trivial costs of stratospheric aerosol injections and the high degree of certainty regarding their artificial cooling effect indicate a degree of leverage that is likely significantly greater than for any other technology.[122] In contrast, other technologies that broadly fall into the category of SG, notably marine cloud brightening and cirrus cloud thinning, currently appear less feasible in technical and economic terms, although the former might play a limited role in local contexts where temperature increases are particularly threatening for vulnerable ecosystems.[123] In addition to managing anthropogenic impacts on the environment and environmental impacts on human societies, climate engineering techniques could, in principle, also contribute to global justice by protecting vulnerable groups and developing countries from harmful environmental impacts. The case of ocean iron fertilization also highlights the importance of legitimate scientific research for contributing to the information commons. Yet, as discussed earlier, climate engineering techniques also imply a variety of perils across all three categories: they can cause different types of environmental harm; they can crowd-out feasible alternatives by deterring deep mitigation; and they can also imply greater *in*justice, for instance to the extent that they imply significant changes in the global land system but also by allowing industrialized countries to shirk their historical responsibility for creating the problem of global warming in the first place.

Institutional responses to the climate engineering challenge show great variety in depth and scope. The LC/LP provides a broad response to marine climate engineering as such (potentially cutting across the divide between NETs and SG) while developing rules of considerable depth for the specific case of ocean iron fertilization. The CBD's response is even broader, implicating all types of climate engineering that might affect biodiversity (arguably all types with the exception of DAC) yet through rules that are unspecific, normatively weak, and not

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associated with any particular mechanisms for monitoring, compliance, or enforcement. The Paris Agreement provides broad normative support for NETs (but not SG), albeit without operational rules for contributing to research, development, or deployment at present, yet with the distinct possibility of the Sustainable Development Mechanism playing a crucial role in the future. Both OSPAR and the LP offer deep regulatory responses to the narrow issue of subsoil carbon storage. In addition, there are two notable instances of institutional *non*-responses: the failure of the United Nations Environment Assembly to follow up on the Swiss climate engineering initiative, and the (at best) marginal attention that SG has received in the context of the ozone regime. Overall, the contributions of these institutions to the realization of promises and to the avoidance of perils associated with climate engineering is patchy at best and inconsistent at worst, especially considering the potential for normative collisions between permissive regulatory approaches (i.e. under the Paris Agreement, OSPAR and the CCS elements of the LC/LP) and restrictive ones (i.e. under the CBD and the marine climate engineering elements of the LC/LP).

The three theoretical approaches used here again offer different perspectives on these outcomes. The *international constellation of interests* tends to be relatively benign. This is particularly the case for NETs, which states (rightly or wrongly) expect to play a major role in achieving international temperature targets. Some NETs would certainly entail costs that are distributed in a highly asymmetrical manner between countries and regions, such as with system impacts from BECCS or possible harm to the marine environment from ocean iron fertilization. These costs remain somewhat hypothetical for the moment while the lack of feasible options for holding international temperature targets without large-scale NETs is widely accepted by the international community. For ocean iron fertilization, there exists a general political consensus to prohibit undesirable and frivolous fertilization schemes that are at odds with the objective of protecting the marine environment from pollution while also creating exemptions for legitimate scientific research. Interests are more difficult to parse for SG. There, states appear to prefer a non-committal hands-off approach, possibly out of concern over potential blowback due to the controversial nature of the technology.[124] This may also explain the failure of the Swiss initiative: lumping SG together with NETs risks contaminating the latter with political controversy and opens the way to restrictive forms of international regulation that might constrain the ability of states to use atmospheric carbon dioxide removals in order to achieve their national emissions targets. While the international constellation of interests for SG is presently rather benign, there are early signs of potential divergence, with the United States recently initiating an interagency programme for coordinating research on SG[125] while most of its international partners, particularly in Europe, arguably continue to be opposed to

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the idea. Generally speaking, though, a rather benign constellation of interests characterizes all of the different types of climate engineering, across NETs and SG, that are currently under consideration. This invariance makes it difficult to explain the variation that is observable at the level of institutional outcomes.

The *normative fit* of climate engineering techniques with pre-existing governance frameworks varies greatly between SG and NETs. Techniques in the former category are generally so dissimilar from anything that international environmental institutions have previously been designed for that there are simply no regulatory frameworks that could easily and intuitively be applied. Beyond the cases discussed herein, there are many other international institutions that might, in principle, have some kind of relevance for different types of SG techniques, including certain protocols to the Convention on Long-Range Transboundary Air Pollution (for stratospheric sulphur injections) or the Outer Space Treaty (for hyper-speculative techniques such as space-based mirrors).[126] Another institution that frequently comes up as a potentially or actually applicable governance framework is the Environmental Modification Convention, a Cold War–era treaty dealing with environmental warfare and weather warfare.[127] The relevance and applicability of these and other institutions is a matter of perspective and legal interpretation, and, in any case, none of them have taken active steps towards developing any sort of SG governance structures. NETs, conversely, have a greater normative fit. The conservation and enhancement of natural carbon sinks has been a component of the international climate regime from the outset, and CCS technology has been under discussion since the early 2000s. The FCCC itself obliges parties 'to mitigate climate change by addressing anthropogenic emissions by sources and removals by sinks'.[128] Ocean iron fertilization is a specific case in that respect. The institutional responses to this technique have primarily addressed it from the vantage point of marine pollution and ocean dumping, while otherwise carving out a regulatory exemption for legitimate scientific research. This research exemption for ocean iron fertilization, moreover, is in line with marine scientific research falling under one of the core norms of the international law of the sea – that is, the freedom of the seas.[129]

From a perspective of *governance object constitution*, the preceding discussion already suggests that the experience with carbon sinks and CCS technology makes it easier to define the properties and conceptual boundaries of NETs than is the case for SG. BECCS, in particular, simply integrates a novel system component, bioenergy, with CCS. DAC, in turn, is conceptually similar to CCS, albeit operating on ambient air, where carbon dioxide concentrations are substantially lower than in flue gas emissions from fossil power stations. In other words, all types of NETs that are presently under discussion have strong conceptual similarities to existing governance objects, making them prone to governance 'as if'. This sets them

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apart from proposed technologies for SG, which are unprecedented and outside the scope of existing cognitive frameworks. The profound difficulty of conceptualizing SG as a governance object may help to explain why it has not been a direct target of institutional responses, with the exception of its indirect coverage under CBD decision X/33 and the potential regulation of marine cloud brightening and measures for the enhancement of ocean surface reflectivity under the LP's marine climate engineering framework. In the case of the failed Swiss initiative at the United Nations Environment Assembly, the proposed (re-)linking of SG and NETs may have proved too unwieldy for governments to process.

The question of which institutional responses would be 'best' for the governance of climate engineering must, in a first step, address whether such responses should entail a unified and overarching governance framework for *all* types of climate engineering (i.e. both NETs and SG), whether NETs and SG should fall under separate arrangements, or whether there is even a need for more fine-grained differentiation at the level of specific technologies. One argument against the 'forced marriage' of NETs and SG is that the two categories entail different political preferences and interest constellations.[130] Splitting them into separate institutional arrangements might thus unlock greater political ambition. At the same time, the intrinsic connection of both NETs and SG to the wider global politics of climate change means that integrated solutions could have greater bargaining efficiency and might enable issue linkages and package deals which, in turn, lead to 'better' cooperative outcomes than would otherwise be possible. If, for instance, NETs are a necessary complement for emissions mitigation, and if SG were to be deployed for time-limited peak-shaving purposes, this creates a strong rationale for an integrative approach that links them within one comprehensive governance framework.[131] At the same time, we should perhaps also not underestimate the potential for divergent preferences and interest constellations *within* each category of climate engineering. For the countries of the Global South, the politics of BECCS, with its reliance on biomass and its implication of large-scale land-use change, look quite different from the politics of DAC, just as littoral states and island states may have specific perspectives on ocean iron fertilization that land-locked countries may not always share. All of this would provide a rationale *against* an integrated governance framework dealing with all types of NETs simultaneously. Given the reasonable concerns about potential negative equity impacts of climate engineering, and particularly of SG,[132] but also bearing in mind questions of bargaining efficiency and the possibility of using linkages for transforming disparate zero-sum issues into an integrated, positive-sum issue 'package', there is a strong case for an integrated institutional response aimed at all types of climate engineering, possibly even inside the climate regime itself, where connections to mitigation and adaptation can be made more easily. For one, this would enable

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some degree of multilateral control, particularly over SG technologies, where concerns over its unilateral deployment, or deployment by small clubs of nations, are especially acute.[133] The integrated approach might also be able to make SG deployment conditional on the achievement of national emissions mitigation targets, thus possibly improving mitigation ambitions.[134] While SG technologies are deservedly controversial, the implausibility of achieving international temperature targets via NETs on the gigaton scale requires an integrated approach that better connects both NETs and SG to the 'traditional' climate regime with its focus on mitigation and adaptation. In addition, a comprehensive integration of climate engineering into the multilateral climate regime would offer enhanced participation and equity, giving voice to developed and least-developed countries that would otherwise have very limited sway over governance outcomes. Particularly for SG, where distributional implications could be more pronounced than for NETs, inclusive multilateralism is a necessary condition for equitable outcomes.

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