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Introduction and Overview

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When the United Nations Framework Convention was negotiated in Rio de Janeiro in 1992, its goal of preventing "dangerous anthropogenic interference with the climate system" seemed well within reach. However, the chief instrument to achieve this goal – the Kyoto Protocol of 1997 – failed miserably. Nearly two decades of negotiations to develop a successor led to the Paris Agreement of 2015, but the voluntary pledges that almost all countries made under it do not take effect until 2020 and the current commitments add up to a world that is very much in the danger zone.[1] The countries promised to come back every five years and do better. Meanwhile, the election of Donald Trump set back US efforts considerably.

Thus a generation after the Rio conference, and after countless meetings and studies, global greenhouse gas (GHG) emissions are much higher, and we have very little time to get them down to safe levels. Keeping global average temperatures well below 2°C (3.6°F) above pre-industrial conditions – the international goal set in Paris – is still theoretically possible but increasingly unlikely. Some serious voices are now saying that, barring a technological revolution, a seismic shift in global politics, or a worldwide economic depression, the only way to avert global climate catastrophe may be climate engineering.

This outcome would not be so bad if we had confidence that climate engineering could be accomplished quickly and without disastrous side effects. However, all the major methods under discussion are either extremely slow or might well cause other terrible problems, and all are unproven at a large scale.

Nonetheless, there is a real chance that in the next few years, someone – perhaps a desperate nation, or a rogue group, or wealthy individual – will attempt large-scale climate engineering. That effort could threaten dire consequences in parts of the world, and we would have all the ingredients for a global conflict.

Hence the need for this book: to assemble in one place what is known about the existing law that is relevant to climate engineering, to identify the open issues, and to describe what a governance structure would need to cover. That way, if the time comes when the world is ready to tackle the problem of actually creating such a structure, or (in a much less pleasant scenario) we are facing immediate choices about deploying these technologies, lawyers and policymakers can be better equipped to make informed decisions.

1.1. WHAT IS CLIMATE ENGINEERING?

The most commonly used definition of "geoengineering" is probably that employed by the Royal Society: "the deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming."[2] We use the term "climate engineering" in the book title simply to avoid confusion with large-scale earth-moving and other activities that do not involve the climate.

Whatever term is used, there are two essential elements: large scale (big enough to affect the climate of the planet or at least regions of it) and specific intent to alter the climate (as opposed to doing so as an unintended side effect, as our industrial civilization has been doing for many years). Virtually all agree that the best way to deal with the climate problem is to reduce GHG emissions; climate engineering arises because efforts to do so have largely failed so far, and there is concern that the planet may be crossing tipping points that will cause irreversible grave damage. Climate engineering might also be attempted in response to a calamitous event, such as a lethally unrelenting heat wave, or the drowning of a city under circumstances that suggested that others might be threatened.

As described in detail in Chapter 2, almost all climate engineering proposals can be divided into two very different categories: solar radiation management and carbon dioxide removal.

Solar radiation management (also called "albedo modification") attempts to decrease the amount of sunlight reaching or staying on the Earth's surface by scattering or reflecting some of it back into space. The most commonly discussed method involves spraying aerosols into the upper atmosphere (using airplanes, balloons, or other means) that would form highly reflective particulates. Another idea is to launch very large numbers of small mirrors or reflectors into a near-Earth orbit. Closer to ground, "cloud whitening" – spraying seawater into the air to make clouds more reflective – could also increase the Earth's albedo. Other variations have been suggested.

Solar radiation management appears to have three major virtues: it is fast, cheap, and reversible. For a cost of perhaps a few billion dollars a year, temperatures might be lowered a degree or two (or more) in less than a year. However, it has a long list of negatives. The principal ones include the following:

- It does not reduce GHG emissions or levels in the atmosphere, and thus does not address climate change's twin threat: ocean acidification, in which carbon dioxide lowers the pH of ocean waters and harms marine life.
- It might disrupt regional weather patterns, and cause droughts in some places and extreme precipitation in others.
- It would alter ecosystems in unpredictable ways by dimming the light, changing the availability of water, and allowing carbon dioxide levels to rise.
- Once begun, it might have to be continued for a long time or indefinitely, because stopping it could cause rapid and disastrous warming unless carbon dioxide levels in the atmosphere had dropped meanwhile.

The best evidence of what solar radiation management would accomplish (for good and for bad) comes from the eruption of Mount Pinatubo in the Philippines in 1991. It injected 20 million tons of sulfur dioxide into the atmosphere, which decreased the amount of sunlight absorbed and lowered global average temperatures about 0.3°C for a period of three years.[3] However, it caused an unprecedented increase in the size of the "ozone hole" and it was followed by floods along the Mississippi River and drought in the Sahel area of Africa that may be attributable to climatic shifts caused by the eruption.[4]

A few ideas have been proposed that could have regional rather than global effects, such as increasing the albedo over the Arctic to reduce melting, or over cities that are suffering from extreme heat. It is not known if these would really work or would have only regional impacts.

The other category of climate engineering is *carbon dioxide removal*. It removes carbon dioxide from the ambient air. (In contrast, carbon capture and sequestration involves removing the gas from an emissions stream, such as that of a power plant, before it reaches the ambient air; since it operates locally, we do not consider it climate engineering.) A wide variety of technologies have been proposed to accomplish this: for example, machines that directly remove the carbon dioxide from the air; fertilizing the oceans with iron filings or other substances that spur algal growth, which absorbs carbon dioxide before sinking to the bottom; creating charcoal that holds the carbon; growing and burning large quantities of biomass for energy, and capturing and sequestering the carbon dioxide; and exposing certain carbon-absorbing rocks to the air in a process called "enhanced weatherization."

A massive program of tree planting might also fall under this category, but it is inherently temporary – trees release their carbon into the air when they die, burn, or are cut down – and it is the subject of separate bodies of law that are beyond the scope of this book.

Carbon dioxide removal is more benign and less risky than solar radiation management. It mitigates the problem of ocean acidification, and it has much less potential for unanticipated side effects. However, at least with today's technology, it appears to be slow and expensive, and may require a great deal of land, and possibly water and fertilizer. It seems that many years of carbon dioxide removal would be required to make much of an impact on global temperatures. Moreover, it is not clear where all the captured carbon dioxide would be held (perhaps in depleted oil and gas reservoirs, coal beds, saline aquifers, or certain kinds of rock formations), whether anyone would want to live on top of these massive gas reservoirs, and how long the gas would stay there. Research is underway to convert the gas to useful or at least easier-to-manage substances. Various technologies are being tested, and it is always possible that the years to come will see a technological breakthrough that enables rapid and inexpensive removal of carbon dioxide with minimal useless residue; however, we cannot count on this happening.

1.2. HISTORY OF CLIMATE ENGINEERING DISCUSSIONS

Humans have imagined altering the weather, and then the climate, for many years. In the 1840s the first meteorologist employed by the US government, James Espy, proposed lighting large fires to make rain through convective updrafts.[5] In 1908, three years after winning the Nobel Prize in chemistry, Svante Arrhenius, the first scientist to calculate how carbon dioxide affected surface temperatures, suggested that burning fossil fuels could help prevent another ice age.[6] In the ensuing decades, there were many attempts to alter local or regional weather patterns, mostly to alleviate droughts. In 1966 the US National Science Foundation produced a report, *Weather and Climate Modification*, followed in 1973 by an update from the National Science Foundation, *Weather and Climate Modification: Problems and Progress*.

An Italian physicist, Cesare Marchetti, coined the term "geoengineering" in the early 1970s to describe the idea of "disposing" of atmospheric carbon dioxide in the deep oceans.[7] Around that time a Russian scientist, Mikhail Budyko, became the first to propose that the Earth's climate could be cooled with the intentional release of aerosols into the upper atmosphere.[8]

Concern about global climate change escalated in 1988 when the United Nations Environment Programme and the World Meteorological

Organization established the Intergovernmental Panel on Climate Change (IPCC). That same year a NASA scientist, James Hansen, famously testified before Congress about the danger that uncontrolled GHG emissions could cause dangerous global warming.

The topic of geoengineering as a solution to climate change remained somewhat taboo, however, until 2006 when Paul Crutzen, who a decade earlier had won the Nobel Prize in chemistry for his work on chemical threats to the ozone layer, published an article entitled "Albedo Enhancement for Stratospheric Sulphur Injections: A Contribution to Resolve a Policy Dilemma?"[9] Important studies followed from the Royal Society in 2009 and 2011,[10] the US Government Accountability Office in 2010,[11] the National Academies of Sciences, Engineering, and Medicine in 2010,[12] and the National Research Council in 2015.[13] A group of more than 100 leading researchers and thinkers met at the Asilomar Conference Center in California in 2010 and prepared a set of recommended principles for research into climate engineering techniques.[14] Several other conferences have followed.

Beginning in 1996 each of the major assessment reports of the IPCC has discussed (though not endorsed) climate engineering and emphasized the risks and uncertainties involved with solar radiation management. However, the IPCC's Fifth Assessment Report (2014) included several scenarios that relied on one form of geoengineering (though not using that term) – bioenergy production with carbon dioxide capture and storage – while stating that the availability and scale of such technologies were uncertain.[15]

The US House of Representatives' science committee held three hearings on geoengineering in 2009 and 2010, and another in 2017. As this is written at the end of 2017, legislation is under discussion but has not yet advanced.

1.3. CLIMATE ENGINEERING IN THE CONTEXT OF CLIMATE POLICY

Climate policy can be seen as having four possible components: mitigation, adaptation, carbon dioxide removal, and solar radiation management. This section describes the four and how they fit together.

Mitigation – As noted above, the principal objective of global climate policy is avoiding "dangerous anthropogenic interference with the climate system." The universally preferred method to do this is reducing GHG emissions (termed "mitigation"). However, though there has been a great deal of activity aimed at reducing emissions, on a global scale it is difficult to point to much measurable success in achieving the desired result. In 1992, the year of the Rio conference, global carbon dioxide emissions were 22.7 gigatons; in 2015 they were 36.2 gigatons – an increase of 59 percent.[16] Global concentrations of greenhouse gases increased from 356 parts per million in 1992 to around 410 parts per million of carbon dioxide in 2017.[17]

There are several reasons why it is extraordinarily difficult to bring down GHG levels in the atmosphere. First, GHGs spread globally very quickly and some (in particular CO_2) persist for hundreds of years, and thus the present ambient GHG levels result from the cumulative emissions of countless sources over the past two centuries. There is a lag between the emissions occurring and the response of the climate system. As Juan B. Moreno-Cruz and David W. Keith have written, "[t]he inertia of the carbon-climate system makes it impossible to quickly reduce climate risk by reducing emissions, as it is expected that 40% of the peak concentration of CO_2 will remain in the atmosphere for 1000 years after the peak is reached."[18] These factors also reduce the incentive for individual actors to lower their emissions, because they would incur the costs immediately and others would reap the benefits in mostly remote times and places.

Second, global GHG emissions (and many other forms of pollution) can be described as the product of three factors: technology, population size, and affluence.[19] Climate policy aims only to affect technology (such as energy source). Many things influence population size, and government policy plays only a limited direct role. Difficult issues of religion, morality, and culture arise whenever government does attempt to influence population size. Affluence is almost universally desired, and it is difficult to imagine a government policy that overtly attempted to reduce it (though of course some policies in some places attempt to redistribute it). Many developing countries have regarded climate policies as efforts to restrain their growth into the affluence enjoyed by the developed world. Some encouraging figures emerged in 2015, suggesting that GHG emissions and economic growth were beginning to lose their tight relationship,[20] but it is too early to tell whether that development will be a long-term trend.

Third, the needed change in technology would entail a massive transformation of the global energy system away from fossil fuels and toward cleaner sources – renewables (such as wind, solar, hydropower, and maybe bioenergy), and possibly nuclear, together with major improvements in efficiency. Though expanding these technologies would yield major benefits in the form of fewer air pollution deaths and reduced environmental degradation from fuel extraction and processing,[21] these advantages for the most part do not appear in national and corporate finances, and energy transformation would cause a great deal of economic dislocation. This dynamic naturally leads to powerful opposition by the interests that would be harmed. Such opposition has played a major role in the paralysis that the United States Congress has experienced in the climate policy area since 1990, and in the policies of the Trump administration.

Fourth, while energy use is responsible for about three-quarters of global GHG emissions, deforestation and agricultural emissions from livestock, soil, and nutrient management cause about one-quarter.[22] The United Nations' REDD program (Reducing Emissions from Deforestation and Forest Degradation) aims to reduce deforestation. As the countries with the largest amounts of deforestation, such as Brazil and Indonesia, have learned, it is very challenging for authorities to control activities in remote areas. Moreover, remaining forest land will face increasing pressures from the rising food demand of growing populations; the sprawl of cities as they expand to accommodate migration from rural areas as well as internal growth; the desire of affluent societies to eat meat, which consumes much more land per unit of nutrition than non-meat products; the use of biofuels as a low-carbon substitute for fossil fuels; and the loss of arable land due to sea level rise and drought.

Adaptation – All the foregoing means that even if the world made its best efforts to reduce GHGs (which it does not), atmospheric GHG levels will continue to rise for at least decades, and climate change will get worse. Thus, in addition to the imperative of mitigation, we also have the necessity of adaptation – efforts to moderate, cope with, and prepare for the current and anticipated impacts of climate change on human and natural systems.[23] For years some policy circles frowned on any discussion of adaptation because it could be seen as an admission of defeat regarding mitigation efforts; but it has become apparent that, under even the most optimistic scenarios, a great deal of adaptation will be needed. In contrast to mitigation, efforts at adaptation can yield short-term and local benefits. However, the places in the greatest need of adaptation to sea level rise, drought, and glacial melt (such as large parts of Africa, Asia, and South America, as well as the small island states) also tend to be the places with the fewest resources to adapt, and the level of international assistance is far below what is needed.[24]

There are severe limitations on what adaptation can accomplish. Houses can go up on stilts, water can be redirected, and crop planting can be adjusted. But while sea walls can hold back ocean waters over very limited areas, protecting entire islands (except for the tiniest) or coastlines of longer than a few miles seems to be prohibitively expensive, and this approach has adverse environmental impacts of its own. Tens or hundreds of millions of people live in the Ganges Brahmaputra Delta, the Mekong Delta, the Nile Delta, the Mississippi Delta, the low-lying islands of the Pacific and Indian Oceans and the Caribbean Sea, and other places that cannot be protected by any sea walls that we can today imagine building. Protracted drought, loss of glacial meltwater, and episodes of unbearable heat will likely make substantial areas unsuitable for much agriculture. Fish stocks may become severely depleted as a result of ocean warming and acidification, as well as other forms of pollution and overfishing.

It is all but certain that much suffering will result from climate change despite efforts to adapt. This dark future in turn has led to demands by the most vulnerable nations for an international mechanism to compensate them for "loss and damage" – what they will endure after adaptation has been insufficient. The topic remains on the United Nations agenda after the Paris conference, but no one can have confidence that any meaningful compensation will be provided, as the wealthy countries cannot be forced to pay.

Carbon dioxide removal (CDR) – This brings us to the third component of climate policy – CDR. Though this fact is perhaps not yet widely recognized, current global climate policy already assumes a great deal of CDR, for without it, achievement of the goal of keeping the increase in global average temperatures well below 2°C (3.6°F) seems to be impossible. (The Paris Agreement also declared an aspiration of keeping the increase to 1.5°C (2.7°F), which would require an even greater amount of carbon dioxide mitigation and removal.) This reality is illustrated by the representative concentration pathways (RCPs) used by the IPCC in making projections under various future scenarios. (The IPCC has no RCP under which the world is likely to stay at 1.5°C.) Table 1.1 shows the four RCPs used by the IPCC, in somewhat simplified form.[25]

In other words, the only scenario under which we keep global surface temperature increases under 2°C relies on extensive use of one form of CDR (bioenergy plus carbon capture and storage, or BECCS). Even keeping to 3°C – a scenario that entails grave consequences – requires large-scale afforestation (i.e., establishing forests or stands of trees where there have previously been none).

Other scenarios have been assessed. The database for the IPCC's Fifth Assessment Report includes 400 scenarios that have a 50 percent or better chance of no more than 2°C warming (with three scenarios removed due to incomplete data). Of these, 344 assume the successful and large-scale uptake of "negative emissions technologies," such as BECCS, direct air capture, enhanced weatherization, or others, and the other 56 assume that global emissions peak around 2010, which did not happen.[26]

TABLE 1.1 *IPCC Representative Concentration Pathways*

Name	CO_2e (ppm)	Likely temperature anomaly over 1850 to 1900	Description	Assumed carbon dioxide removal
RCP 8.5	>1000	> 4°C	Business-as-usual growth	None
RCP 6.0	850	4°C	Stabilization without overshoot	None
RCP 4.5	650	3°C	Stabilization without overshoot	Large-scale afforestation
RCP 2.6	450	2°C	Peak before 2100 and then decline	Bioenergy with carbon capture and storage (BECCS), leading to negative emissions

Source: Intergovernmental Panel on Climate Change, Climate Change 2014: Synthesis Report Summary for Policymakers (2014), Table SPM.1, www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf.

The need for negative emissions is implicitly embedded in the Paris Agreement, which declares that:

> [i]n order to achieve the long-term temperature goal [of less than 2°C with an attempt to keep to 1.5°C], Parties aim to reach global peaking of greenhouse gas emissions as soon as possible … and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century.[27]

The reality is that, if the temperature goal is to be met, any substantial continued use of fossil fuels in the second half of this century will require a great deal of CDR. Fossil fuel use emits about 32 gigatons of carbon dioxide per year. Other sources, such as methane leakage, cement manufacture, and other industrial processes, add another 5–7 gigatons carbon dioxide equivalent. Deforestation and agriculture, forestry, and other land use changes (but subtracting emissions sequestered by forest growth) add yet another 10–12 gigatons a year. This all adds up to about 49 gigatons. However, global carbon sinks remove only about 18 gigatons per year (8.8 to the oceans, 9.2 to land, not including land use changes).[28]

Thus the sinks take up about the equivalent of the non-fossil sources. To achieve a "balance" between emissions and sinks, we need to just about end the release of GHGs from fossil fuels unless there is a radical increase in sinks or reduction of non-fossil fuel emissions. This shift would have to be achieved well before the end of the century. One study suggests that carbon dioxide from electricity generation would have to be brought close to zero by 2050, and by then around 25 percent of energy required for transportation would also need to come from electricity (up from less than 1 percent now).[29]

There seem to be only three ways to continue to use fossil fuels for electricity in the second half of the twenty-first century (and for transport by the end of the century) and still meet the temperature goal, and it appears we would need to implement all three on a large scale:

- Capture the carbon dioxide from power plants and other large industrial sources before it escapes into the air, and utilize or sequester it
- Initiate a massive program of CDR from the ambient atmosphere
- Create new sinks, such as through the immediate halt to deforestation and a worldwide program of tree planting.

All three of these methods raise a question of how long the carbon will be stored; we do not know how long carbon will stay in reservoirs. We do know that trees do not live forever, and when they burn or die, they release their carbon. Moreover, most methods of CDR, when deployed at a scale necessary to stay within 2°C, would require extremely large amounts of one or more scarce resources – land, energy, water, nutrients, and investment capital. In view of these resource demands, serious questions have been raised about the feasibility of removing sufficient carbon dioxide from the atmosphere to avoid dire consequences.[30] The technology that is receiving perhaps the greatest attention, BECCS, which involves producing large amounts of biomass from fast-growing trees, switchgrass, agricultural waste, or other sources, burning it in power plants, and capturing and storing the carbon, is still in the development stage, and there is not yet the assurance that this approach (or any of the other negative emissions technologies) can be performed economically at scale.[31]

Solar radiation management (SRM) – It is still possible, at least theoretically, that in the next few decades the world will engage in sufficient programs of mitigation, adaptation, and CDR to prevent the widespread damage that can be caused by severe climate change. Some technological breakthrough may be our best hope of this. After all, the technology of hydraulic fracturing, which had been under quiet development for decades, burst forth in the late