# Negative Emissions: The future promises and policy challenges of Carbon Dioxide Removal technologies

A dissertation presented

by

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And to my friends and loved ones around the world, who stand as a reminder that positive impact is created by both small and large deeds - This is for you.

## Abstract

This papers aims to explore future policy challenges and promises of carbon dioxide removal (CDR) technologies. The investigation is motivated by needs to drastically reduce $CO_2$ concentration levels in order to mitigate future harms caused by global warming. Here the focus is on the potential of using CDR as a global solution. By applying general public policy theories and by using analogues drawn from solar radiation management and its policy challenges, the paper explores both ethical and practical obstacles to the mass implementation of CDR. Some of the analysis looks at cost-benefit analysis frameworks, the precautionary principle, the Collingridge dilemma, concerns surrounding research, regulatory mechanisms, and issues relating to funding and resource allocation. The findings show that while there are clear challenges, CDR technologies show enough promise to warrant further research and eventual implementation, especially within the context of current and worrying $CO_2$ concentration trends.

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## Introduction

The 2014 United Nations Climate Change Conference in Lima (COP20) ended on a high note, with both developing and industrialized nations pledging to curb emissions and reaffirming the overarching goal of stopping the global average temperature from reaching 2 °C above pre-industrial levels (UNFCCC, 2014). Additionally, the newly formed Green Climate Fund, which is designed to help developing countries in climate change adaptation and mitigation practices, is set to receive $10 billion after being given pledges from 27 countries worldwide (Green Climate Fund, 2014). Despite these signs of progress and rising hope for COP21 in Paris 2015, the year 2014 was recorded to have the highest release of carbon dioxide since the dawn of the industrialized age (Global Carbon Project, 2014), this also coincided with the highest temperatures in recorded history (National Climatic Data Center, 2014).

Climate change is one of the largest threats to our world, it endangers economies, risks displacing millions of people, and threatens to damage ecological systems beyond measure. For the past few decades the discourse on solving climate change has steered around notions of prevention and mitigation. Despite international discussion on global governance and solutions for climate change, no binding nor universal agreement has been reached. Recently, the scientific consensus has been that policy frameworks built around prevention received too little support and were acted upon too late. There may even be evidence that some global warming will occur even if emissions are cut down to zero by tomorrow (Frölicher et al. 2013). In the wake of this shift, political focus has moved towards adaptation on local instances and mitigation on a global scale, mitigation being of the utmost importance. While climate impacts will still occur, substantial mitigation is necessary for halting rampant temperature increases. Without mitigation, the needs placed on adaptation will grow more dire, widespread, and increasingly difficult to implement.

In terms of mitigation techniques, both mainstream media and political actors have focused on cutting emissions and converting to green energy sources, however the nascent field of geoengineering is starting to show itself as a complementary tool which could prove useful in the century ahead. Geoengineering is in short, "the deliberate large-scale intervention in the Earth's natural systems to counteract climate change". It includes Solar Radiation Management (SRM), which is the process of [reflecting] a small proportion of the Sun's energy back into space" and thereby reducing global temperatures, and Carbon Dioxide Removal (CDR) which aims to "remove carbon dioxide from the atmosphere, directly countering the increased greenhouse effect and ocean acidification" (Oxford Geoengineering Programme). Given complex interactions and feedback systems within Earth's climate, many have cast doubts on geoengineering as a whole, especially SRM techniques. Unforeseen consequences, ethical dilemmas of trying to impact the climate on a global scale, and problems arising in terms of politics and practical implementation are some of the critiques commonly used against SRM. The concerns for CDR have however been less topical, as the field is still largely unexplored in terms of scientific research, policy proposals, and private ventures. It is only recently that serious interest for CDR has emerged, but even so at this stage its mass implementation is something of speculation.

With this in mind, this paper will explore the potential policy challenges for the mass implementation of CDR technologies. It will do so by reflecting the dire needs for meaningful climate policies as shown by the IPCC's 5$^{th}$ Assessment Report and by assessing obstacles found

within several geo-political dimensions and its stakeholders. The aim of the paper will be to capture the key points surrounding CDR, discuss both possibilities and limitations, and create a brief summary for policy makers.

The underlying thesis is that mass implementation of CDR is a plausible policy direction with potential to serve as a valuable tool in helping the mitigation of the harmful effects stemming from global warming. This is especially significant given rising emissions as seen by developing countries and failures of many industrialized nations to adequately curb emissions. The nature of CDR and its capacity for 'negative emissions' makes it an appropriate method to counteract these sort of trends by providing further emission reduction tools applicable on a global scale. However, before any future implementation, additional research is needed on scientific, philosophical, and practical grounds in order to gauge and minimize harmful spillover effects and ensure that CDR technologies help the overarching fight against global warming instead of detracting from it.

Given the emergence of CDR as an academic topic and more broadly speaking a public policy area, some of the analysis will be drawn from parallels with SRM techniques and its policy challenges. Additionally in areas where there is a lack of research, this paper will aim to adapt general public policy theories and apply them directly to CDR. Due to size restrictions this paper will not be able to go beyond a mere overview of CDR issues. Most of the problems and solutions presented within could be expanded upon with additional research. Lastly, while there are a number of greenhouse gases, this paper will only look at carbon dioxide emissions and concentrations.

For any policy treatment, four areas generally need to be discussed:

- The status quo and the need for new policies.
- Mechanisms and potential implications of these policies.
- Challenges and problems related to the policies
- Ways of overcoming these challenges.

As such the primary areas of investigation will include an overview of the needs for comprehensive and meaningful climate policies on a global scale. Thereafter there will be an explanation of CDR techniques and how they could fit into a global solution. Following that ethical and practical concerns will be assessed in relation to future policy creation and implementation. Afterwards the findings of the paper will be discussed accompanied by concluding thoughts.

## Dangers of Global Warming in the 21$^{st}$ Century

The global consensus on climate change mitigation has increasingly become one of taking preventative steps to ensure that the global temperature increases do not surpass 2°C by the end of this century compared with pre-industrial standards. This growing agreement of an 'acceptable' future has come about much due to increasing evidence highlighting potentially devastating effects of rampant climate change and pragmatic thinking. Most prominently the IPCC's 5$^{th}$ Assessment Report included four Representative Concentration Pathways (RCPs) showcasing different trajectories based on future greenhouse gas concentrations. The importance of these type of scenarios and projections should not go unnoted. While some might claim that they perpetuate needless hysteria and are driven by fear mongering, scenarios have an important role to play in policy making. With them different stakeholders can understand the causal links between drivers

and outcomes. Allowing them to plan and engage with issues and ask the question of 'what future do we want to end up with?' (Ringland, 2002: 133). In the case of climate scenarios, the quality of the narratives and supporting evidence is key to ensure that various actors understand the gravity of the processes occurring within the Earth's systems (Ibid.: 132). Once understood, scenarios can become an important part of the strategic management to tackle issues. In many cases fostering engagement between participants and providing shared context within areas of scope, outputs, and range of impacts (Ibid.: 137-141).

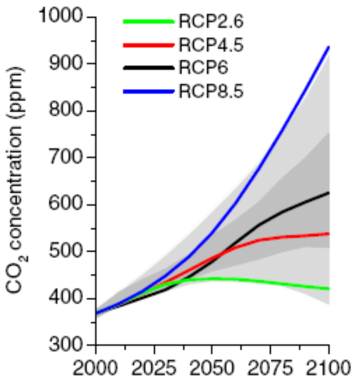
The Representative Concentration Pathways, for instance, are based on the possible ranges of radiative forcing values quantified in units of watts per square meter of the Earth's surface or in other words heat incident on Earth. Here RCP 2.6 represents a +2.6 W/m$^2$ by the end of the century compared to pre-industrial values and so forth. As shown in Table 1, each scenario presents its own impacts on the global temperature and average sea levels. For the sake of context the global temperature has already risen by roughly 0.8°C since 1906 and has been increasing with growing global industrialization. (IPCC Fourth Assessment Report, 2007: 244).

| Scenario | 2046-2065 | | 2081-2100 | |
|---|---|---|---|---|
| Mean and likely range | Global temperature increase (°C) | Global mean sea level increase (m) | Global temperature increase (°C) | Global mean sea level increase (m) |
| RCP 2.6 | 1.0 (0.4 to 1.6) | 0.24 (0.17 to 0.32) | 1.0 (0.3 to 1.7) | 0.40 (0.26 to 0.55) |
| RCP 4.5 | 1.4 (0.9 to 2.0) | 0.26 (0.19 to 0.33) | 1.8 (1.1 to 2.6) | 0.47 (0.32 to 0.63) |
| RCP 6.0 | 1.3 (0.8 to 1.8) | 0.25 (0.18 to 0.32) | 2.2 (1.4 to 3.1) | 0.48 (0.33 to 0.63) |
| RCP 8.5 | 2.0 (1.4 to 2.6) | 0.30 (0.22 to 0.38) | 3.7 (2.6 to 4.8) | 0.63 (0.45 to 0.82) |

Table 1: Representative Concentration Pathways & Effects

Source: IPCC Fifth Assessment Report WG1, 2014

Some underlying factors of the RCPs is that of $CO_2$ concentration and emissions into our atmosphere. With this in mind, a global $CO_2$ concentration target of 450 parts per million by volume (ppm) has been set for the end of the century. As shown by Figure 1, this would mean that the global community would have to find itself somewhere between RCP 2.6 and 4.5. Which corresponds with substantial cutbacks in $CO_2$ emissions as seen in Figure 2. As it stands, the world is over 80 percent reliant on fossil fuels for energy needs and with global economic growth the rate of carbon emissions has risen. Studies have shown that $CO_2$ concentrations have risen on average 2 ppm annually from pre-industrial levels to nearly 400 ppm today (Lynas, 2011: 52), with pre-industrial levels being estimated around 260-270 ppm in mid-to-late 19$^{th}$ century (Wigley, 1983).



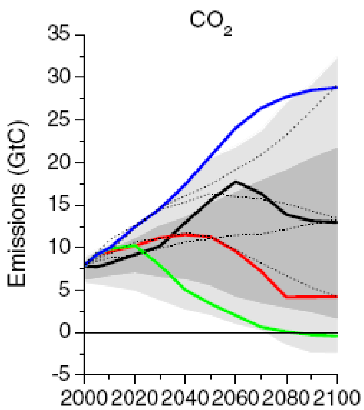




Figure 1 (left): $CO_2$ concentrations trends

Figure 2 (right): $CO_2$ emission trends

Source: van Vuuren et al., 2011

The importance of $CO_2$ concentrations is due to its role as a driver of the greenhouse effect and global temperatures in general. Not only is it the second largest greenhouse gas contributor after water vapor but is it also primarily emitted through human activities (Kiehl and Trenberth,

1997). While a target of 450 ppm might set us on the course of experiencing a 2°C increase by the end of the century, even this is not without its problems. With any change there are winners and losers. Because the amount of losers increase with higher concentrations many have instead strongly advocated for a target of 300 ppm and an upper safety limit of 350 ppm. Reasons for these targets include allowing wildlife and ecosystems to properly adjust to climate change, something which becomes increasingly difficult at our present course, where a substantial number of extinctions are expected to occur. (Thomas et al., 2004). Additionally, lower $CO_2$ concentrations have the potential of restoring the Arctic back to health and prevent the destruction of mountain glaciers that provide water to millions worldwide (Lynas, 2011: 59). As of right now, negative emissions would be required to reach these targets.

Furthermore there are effects that could worsen in the future as many climate systems work based on thresholds and tipping points, and our current path is dangerously close to many of them (Sample, 2005). For instance, during the 2003 European heatwave, researchers saw "a 30 percent drop in plant growth across the continent" due to photosynthesis shutting down because of drought and abnormal temperatures. It was discovered that plants actually started emitting $CO_2$ instead of absorbing it, releasing almost half a billion tons, estimated to be "equivalent to a twelfth of total global emissions from fossil fuels" that year (Lynas, 2008: 59-60). Causal links between temperatures and further emissions from unexpected areas suggest that higher temperatures will give rise to additional emissions which in turn will further amplify the effects of global warming. Potentially leading to rampant global warming (Cox et al., 2000). The climate system could gain additional momentum if unpredicted factors come into play, including the destruction of rainforests and the release of additional soil-bound greenhouse gases that were previously locked in tundra areas. Studies have shown that these effects could increase $CO_2$ concentrations by an extra 250 ppm by 2100 thereby increasing global warming by an addition 1.5°C (Ibid.).

At the extreme, rampant climate change would prove devastating. Adaptation efforts would become increasingly difficult to achieve. Impacts include agricultural failure due to flooding or drought, increased ocean acidity, rising sea levels, and geo-political consequences with the potential of climate refugees and conflicts over resources. These effects become increasingly problematic as we move closer towards a 5°C increase by the end of the century. In most regards a temperature increase of such magnitude would mean the end of civilization as we know it. Given positive feedback loops, at these levels large areas would become uninhabitable due to flooding, extreme temperatures, and desertification. Most coastal cities would have to be abandoned, there would be mass migration towards Earth's poles, and on an ecological level this would lead to a mass extinction of animal and plant life around the globe (Lynas, 2008: 208-214).

Despite a growing consensus and acceptance of climate scenarios, the status quo still faces a number of issues that make political accords difficult to reach. For instance, the global South's desire for higher standards of living through conventional development means and the global North's failure to abate emissions were at the core of Copenhagen's Climate Conference. A conference that many would name a 'fiasco' for failing to meet its own 'meaningful' targets (Foster, 2015: 6). While this is a heated topic, the takeaway is that future climate policies will be characterized by increasing complexity and diversity within the global community. Even now new patterns of interaction and linkages between domestic and external arenas are forming. And as seen

with climate scenarios, unpredictable spillover effects threaten to endanger vast areas outside one's own national reach (Parsons, 1995: 234-235).

Within conflicting and overlapping interests, both for nations and private enterprises, the need for coordination and compromise has never been more essential. Here climate policies must find solutions amicable to multiple parties (Young et al., 1997: 272). Any future environmental policy direction and its international regime must establish common problem definitions, a range of implementable policies, and have well-structured evaluation mechanisms (Ibid.: 115). The last aspect is key as negative consequences in terms of economic costs have only recently been included in the design of international climate regimes (Ibid.: 139). Apart from this, compliance with international regimes must be fostered from "a favorable alignment of actor's beliefs, interests, and capabilities" (Ibid.: 116). Notable developments of this kind would include the creation of Green Climate Fund which is designed to assist developing nations with adaptation and mitigation practices. More recently, the 2014 UN Climate Change Conference in Lima ended with a call for action which takes into account different national needs and capabilities (UNFCCC, 2014).

Even with these positive developments it is vital for future environmental policies to adhere to the demands of today's world. In regards to these needs they could be summarized within three primary areas:

- First the policies of tomorrow need to have the ability to meaningfully tackle climate change, both in terms of adaptation and mitigation. Without impactful actions, the IPCC has stated that "the net damage costs of climate change are likely to be significant and to increase over time" (NASA).
- Secondly, the approach to these policies must stem from a technical point of view. As climate change is "the result of human beings generating energy by burning hydrocarbons and coal… it is a technical problem… driven by politics" (Lynas, 2011: 66). While there is room for debate concerning moral issues such as the value assumptions of different ethical stances, the downsides of growth, and questions of need vs. greed. This paper will take the position that climate change ought to be tackled as an engineering project. Given existing social, cultural, economic, and political norms and the urgency for action, this approach seems less likely to encounter large resistance compared to alternatives that require fundamental changes to human society and our general perception of the world. If done correctly, it could in fact foster economic growth and innovation within existing frameworks while allowing us to achieve carbon-neutrality and eventually carbon negativity (Ibid.: 70).
- Thirdly, polices need to inspire voluntary participation from its stakeholders. This includes overcoming difficulties in coordinating economic and environmental regimes, which could succinctly be summarized as a problem of "structural incommensurability", where "environmental regimes have clear economic impacts" but "their [structures are] not defined by these economic impacts" (Young et al., 1997: 271). To fix this, regimes need to be created in mutual beneficial and supporting ways so coordination becomes desirable. However in areas where this is not possible, environmental regimes ought to take precedence while trying to mitigate detrimental impacts on economic regimes (Ibid.) Furthermore within the goal of building willing participation there needs to be a "high degree of accountability to ensure that burdens are fairly shared." (Ibid.: 265) More

specifically different approaches and technologies should be adapted to meet the needs and special circumstances of nations (Lynas, 2011: 70).

Whether the goal is reaching a $CO_2$ concentration of 450 ppm or the more desirable 300 ppm, any course of action will generally need to meet these criteria in order to facilitate meaningful climate impact. This alone will be the greatest challenge of COP 21 and for climate actions afterwards. Part of the transition towards finding solutions to these challenges will have to come from scientific and innovative endeavors. With this in mind, the remainder of this paper will discuss CDR as one of these technologies.

## Explanation of CDR Techniques

The basic science of CDR techniques rests on the idea of creating 'carbon sinks' either through natural processes or by artificial means. These sinks would then absorb $CO_2$ from the atmosphere by converting it into biomass or storing it by other means. The grand idea behind negative emissions is that with enough removal of $CO_2$ the Earth's systems would allow for a potential reversal of global warming and begin the recovery of ecosystems. In less optimistic views, it could at the very least help stabilize global warming and prevent run-off temperature rises.

Academically, geoengineering and in particular CDR is still emerging. The size of the field is restricted to a few dozen research institutions and a small number of researchers. Politically, geoengineering has been viewed as a wild card and a last resort to the climate question. This view has mostly stemmed from the primary research area of geoengineering, that of Solar Radiation Management and the large uncertainties and risks its implementation might entail. However, more recently negative emission methods have gained larger prominence by being included in works such as the OECD's Environmental Outlook to 2050' report (OECD, 2012). CDR methods such as bio-energy with carbon capture and storage (BECCS) as well as afforestation have also been included in the IPCC's 5$^{th}$ Assessment Report. (For descriptions of CDR methods and for the basket of technologies that will be explored in this paper view table 2.)

Table 2: CDR methods & descriptions

| | |
|---|---|
| ***Afforestation.*** | Engaging in a global-scale tree planting effort. |
| ***Biochar.*** | 'Charring' biomass and burying it so that its carbon is locked up in the soil. |
| ***Bio-energy with carbon capture and storage. (BECCS)*** | Growing biomass, burning it to create energy and capturing and sequestering the carbon dioxide created in the process. |
| ***Direct Air Capture*** | Building large machines that can remove carbon dioxide directly from ambient air and store it elsewhere. |
| ***Ocean Fertilization*** | Adding nutrients to the ocean in selected locations to increase primary production which draws down carbon dioxide from the atmosphere. |
| ***Enhanced Weathering*** | Exposing large quantities of minerals that will react with carbon dioxide in the atmosphere and storing the resulting compound in the ocean or soil. |
| ***Ocean Alkalinity Enhancement*** | Grinding up, dispersing, and dissolving rocks such as limestone, silicates, or calcium hydroxide in the ocean to increase its ability to store carbon and directly ameliorate ocean acidification. |

Source: Adapted from Oxford Geoengineering Programme

Out of these CDR approaches, ocean fertilization remains generally untested on large scales. Research results are currently inconclusive as to their viability (Doyle, 2012). Enhanced Weathering & Ocean Alkalinity Enhancement find themselves in similar stages of investigation with further research needed to fully evaluate their environmental impacts and costs effectiveness (Renforth, 2012). Ocean-related CDR methods are those that raise the most concerns, despite this they will be included in the coming discussion for a more complete overview of CDR policy challenges.

In terms of commercial application, Sir Richard Branson's Virgin Earth Challenge is perhaps the most known example of efforts to jumpstart private initiatives on CDR. With a cash prize of $25 million and thousands of initial proposals, the remaining 11 finalist each show promise of creating CDR products that could be scaled up to have global impact. Some of the finalists include Carbon Engineering, a direct air capture company led by the prominent geoengineering scientist David Keith, the Swedish BECCS company Biorecro, and the Savory Institute, led by Allan Savory in aim of healing grasslands by means of managed livestock (Virgin Earth Challenge). In regards to scale, it should be noted that any meaningful impact would have to come from a mass implementation of CDR that could bear costs comparable to existing industrial sectors - an issue that will be explored later on.

Despite this, the importance of CDR should not go unspoken for, while it might seem counterintuitive to focus on technologies that remove $CO_2$ from the atmosphere instead of focusing on cutting emissions. CDR could work to compensate for industries and geographic regions where carbon abatement is difficult – Essentially shifting the burden for countries that will need to use fossil fuels in the near-term future. It also goes without saying that fixing 'end of pipe' problems or the sources of pollution is still necessary even with CDR. Within the larger context, many of the IPCC climate scenarios already rely on two forms of CDR, that of afforestation and BECCS. The questions that remain are those of costs, negative consequences, regulatory mechanisms and the ethical implications of geoengineering (IPCC Fifth Assessment Report, 2014: 419).

## Ethical and Theoretical Concerns

Geoengineering has left people uneasy in the past and with a number of ethical concerns it is easy to see why. Within this section the consequences of cost-benefit analysis frameworks, the precautionary principle, and problems arising from the Collingridge dilemma will be applied to CDR techniques. Many of them highlight critical issues that need to be assessed before considering more practical implementations of these technologies. While some of these concerns apply to certain technologies more than others, they are still important to address when looking at CDR techniques as a package. Additionally, this section will highlight how many of the ethical considerations are related to one another and provide a complementary assessment of CDR related concerns.

### Cost-Benefit Frameworks

There are a number of questions that need to be asked when evaluating CDR approaches with cost-benefit analysis (CBA) frameworks. Since the beginning of environmental policy discussion there has been discord between economists and environmental thinkers. The idea of placing a value on nature and its components has been central to such disagreements. Regardless of whether nature holds intrinsic value or an economic value to humans, the modus operandi of environmental policies and assessments have nearly always used some form of CBA. Practically, this allowed for policies to discern costs and benefits in a tangible manner that makes sense from economic and political perspectives. However these metrics have had a tendency to undervalue nature and its benefits (Beder, 2006: 134).

To see why, one needs to look at how these calculations are made. Many CBA calculations work under normative economic approaches, meaning they are driven by value systems that tend to promote one thing over the other. Tangible and quantifiable metrics such as economic output and efficiency are commonly used, as opposed to intangibles notions of fairness, quality of life, and other ethical concerns (Parsons, 1995: 401-402). Common methods of finding the values of natural resources include using contingent valuations, in which values are estimated from the prices people are willing to pay to conserve nature or the prices they are willing to accept for losses of environmental features. Another method is weighing opportunity costs by comparing different configurations of resource usage (Beder, 2006: 135-136). It should be noted that these frameworks are, from a theoretical standpoint, artificially constructed and in practice often reinforce calculations and norms that treat nature and the economy as separable entities which can sometimes be detrimental to both (Foster el al. 1997). Nevertheless as environmental policy making has evolved, these type of metrics have been included in environmental impact assessments, directly highlight environmental concerns with specific scientific evidence and public opinion in mind (Holder, 2004).

Their relation to CDR could be explained as follows: Given that policies are created within the contexts of socio-economic, geographical, and cultural constraints. The value judgments policy makers subscribe to, will "constitute the boundaries of what is possible and desirable – of what is and ought to be" (Parsons, 1995: 207). This implicitly means that value judgments influence the way policies are shaped and subsequently how they are implemented. This raises several potential concerns. Firstly, CDR and its capacity of negative emissions could create a policy climate and CBA calculations in which delays with mitigation efforts are seen as acceptable. This could extend our climate limitations and allow for more polluting to occur. However if strong norms exist, moral hazards do not seem likely. This would depend on how we use CDR, for instance mass implementation would conceivably avoid the problems of 'indulgences' which are common criticisms of carbon offsetting schemes. However with policy decisions there are nevertheless tendencies of pushing costs and discounting future generations (Beder, 2006: 145). As shown by climate studies, delays in mitigation efforts would only worsen the situation and increase costs as time goes on – something that must be avoided (NASA).

Secondly and more technical grounds, there is the possibility for a lowering of negative externality costs of pollution within higher ranges of 'acceptable' carbon emissions if CDR becomes commonplace. This could happen due to extensions of previous pollution boundaries, thereby reducing the pressure on actors on edge of the former boundaries. This could be harmful as, higher carbon concentrations leave the actual impact of removed $CO_2$ at a constantly decreasing rate (Policy Exchange UK, 2013.) As previously explained, with climate thresholds, damage will still occur despite CDR usage at high carbon concentrations. Lastly, based on the means by which CDR impacts are valued there are several possible conflicting interactions with existing environmental norms and mechanisms. These include global or regional carbon markets and international carbon accountancy. With CDR adding another dimension to pollution discourse, careful evaluation must ensure that the way in which CDR impacts are valued is compatible with other adjacent systems and is measured in a way that does not undermine needed mitigation efforts.

Another question is whether we want CDR to fall into CBA mechanisms and more generally problem solving approaches. If CDR can transform climate trends, it needs to be asked whether it

ought to be confined within calculative, compromising, and often profit-driven frameworks. Depending on scales of CDR impacts and how they are calculated, for instance used as a means of improving a nation's carbon accountancy or from the perspective of global carbon concentrations, its implications vary. On local scales CDR could end up becoming another tool to expand national limits, while on a global scale it could be used to push climate thresholds. However given the dire nature of climate change, how do you calculate the amount of CDR that ought to be used in relation to other socio-economic constraints? What is the cost of 5°c or 6°c increases and in extreme cases the end of human civilization as we know it? At these scales and costs, most conventional means of CBA seem to lose relevance. The willingness to pay to avoid such outcomes would seem to be infinite and the opportunity costs immeasurable – In such cases CDR usage would become a given. While individual CBA calculations might make sense on local instances and even cumulatively to estimate impacts on larger systems (Beder, 2006), the existence of climate thresholds make them difficult to use on global scales. It could be argued that, "ecological systems are not like economic systems where you can plot trends in smooth continuous lines. Rather, such systems may be able to withstand many small assaults and then collapse suddenly once a threshold is crossed". In these cases other means of ethical judgment might be more valuable in assessing CDR (Ibid.: 154).

## The Precautionary Principle

Here the Precautionary Principle could play a role. The principle states that any action that is associated with a suspected risk should not be taken unless there is a consensus deeming the action of acceptable harm. A burden of proof which falls upon those taking the action. This notion could apply to CDR as we must ask whether CDR presents low enough risk to deem it usable. This question raises an important aspect of policy making, that of risk management. In cases of technologies that could potentially impact the world, any degree of uncertainty may lead to devastating consequences. The norm within environmental policy making has been to make decisions in conjunction with scientific experts who are able to present clear and supported recommendations (Ibid.: 56). If actions are known to have high risks then preventive actions are used, but in cases where there are large uncertainties precautionary actions are used instead (Ibid.: 47). Given the onus on actors to show that their actions present little danger or acceptable risk, questions of what constitutes acceptable risk arises (Ibid.: 50). In many cases uncertainties are linked with lacking data or understanding of causal relationships (Ibid.: 56-57). But how much evidence is needed before precautionary action can be relaxed?

When considering CDR, impacts affecting entire ecosystems need to be accounted for, for instance what is the probability of ocean fertilization having negative impacts or how safe are the carbon storage mechanisms of direct air capture or BECCS? To answer these questions the burdens of proof tend to use specific criteria. Requiring actions to have support from our background knowledge and theories, to be explicable in terms of scientific facts and show causal relationships either by analogy to similar mechanisms or explicit proof. It is also advantageous if impact predictions are reasonably precise and have supporting historical precedents showing a range of risk (Ibid.: 61). Additionally there are questions of who constitutes the consensus? Who owns the atmosphere, the oceans, and so forth? Are there unknowable harms? And do humans have the right to steer the course of the planet? On the other hand, timing is also a crucial component, given the increasing costs of delaying the use of CDR complete risk and ethical assessment might not be feasible nor even desirable. Thorough testing might take too long and some effects might only be

seen as experiments reach larger scales. As environmental policies encounter conflicts with scientific uncertainty and urgency of taking action, it might be better to use the precautionary principle to find acceptable boundaries of environmental and economic risk thereby allowing actions to be taken (Young et al., 1997: 265).

## The Collingridge Dilemma

But even outside direct scientific uncertainty, information regarding emerging technologies plays another role within the socio-political fabric of decision making. In his 1980 book, The Social Control of Technology, David Collingridge presented a problem associated with emerging technologies and how they interact with society. He showcased a double-bind scenario in which two problems emerge. First an information problem occurs in which the impacts of technologies cannot be easily predicted until wide implementation has occurred. On the other hand, a power problem appears once technologies have been widely implemented making the control of them difficult. (Collingridge, 1980: 16-21). By applying the 'Collingridge Dilemma' to CDR new concerns emerge.

Starting with the information problem. When dealing with new technologies and plans to implement them, the future social impacts are never entirely apparent. Despite efforts of risk management and using metrics such as the precautionary principle, there will always be a range of uncertainty. In the context of technologies that could impact a vast number of stakeholders, concern is warranted. With other forms of geoengineering such as Solar Radiation Management, there are risks that nations might use them to create favorable climate conditions within their own domains. The concern here is that large interventions in the atmosphere, by use of sulfates, could impact entire continents through unilateral action (Hulme, 2014). While CDR methods might not have the same direct effect on temperatures, there are unforeseen social consequences that need to be accounted for. BECCS for instance would demand an increase in the use of biomass as a fuel source, putting more pressure on the already existing 'fuel vs. food' debate. Other CDR methods involving the ocean as a carbon sink have the potential of negatively impacting several countries using the same waters, even if it was used unilaterally. These type of questions are hard to resolve as modelling and predictors often fail to account for social interactions.

Furthermore, depending on the social view of technological solutions multiple scenarios can unfold. In some cases, technologies might be rejected and receive political backlash due to people's discomfort with geoengineering. Much like the case of the 2011 British 'Stratospheric Particle Injection for Climate Engineering' experiment (Marshall, 2011). Under other circumstances moral issues might be reckoned with and technologies could be used to a lesser extent. Alternatively, there is also the possibility of subscribing to techno-optimistic views, in which technologies are accepted and applied by modifying or ignoring current moral frameworks (Hoven et al., 2014: 27). These three scenarios present potential routes for the social interactions with CDR and each carries certain consequences. All-out rejection might rob the world of necessary technical solutions while blatant techno-optimism might carry excessive risk - caution is undoubtedly needed when one still has control over the technological development of CDR.

Much like with other socially controlled technologies, if CDR became commonplace it runs the risk of becoming entrenched within political systems and the minds of people, with that regulations and changes to CDR could grow ever more difficult to enact. This problem persists

primarily due to three reasons. As previously mentioned, there are concerns that limits on industrial output get extended due to social and political perceptions of CDR, allowing for wider emission leeway or 'indulgence' situations in which polluters see CDR as a way of counteracting costs of emissions. Secondly, it is conceivable that the CDR industry, with its large estimations of capital value, could become an actor with its own political clout. If this were to happen, there are risks of inefficiencies, tampering with figures and data, slowing down policy changes, and generally acting in CDR industrial interests, which has been the case for many large sectors in modern history (Collingridge, 1980: 147-158). Lastly, there is a risk of removing political capital from alternative solutions. Given the complexity of environmental policies, a multitude of actors, and constraints based on political, economic, and social factors, policy makers can only achieve so much before encountering resistance. On limited budgets it might be difficult to defend large investments into CDR, adaptation, or other mitigation efforts simultaneously. The ideal situation might be the one in which CDR is used as a countermeasure for sectors where emission abatement is difficult while other environmental technologies focus on end of pipe problems. As the IPCC pointed out, with lower near-term mitigation efforts future policy courses would have to rely more heavily on CDR technologies, thereby exposing greater risks and uncertainties. As such a balance seems prudent (IPCC Fifth Assessment Report, 2014: WG3, 478). The risk of removing political capital from other viable options is real, whether this involves supporting other technological solutions, cutting emission, or advocating for large social changes to combat climate change.

With this in mind, the Collingridge Dilemma shows us that our interactions with technologies, especially once they become entrenched, run a risk of preventing us from reaching other outcomes that would have been open if we had avoided entrenchment. Generally "the social controls that make technology possible do not automatically interact in such a way as to produce the best available outcome" (Schwarz and Thompson, 1990: 107). This highlights a common problem with predicting the adaptation of technologies and calls for the need of having "an understanding of the whole system… and how these technologies will be implemented and fit into the system" (Ringland, 2002: 229). However, the actual implementation of CDR presents its own challenges beyond theoretical concerns.

## Practical Challenges of CDR Implementation.

When discussing the practical implications of CDR implementation it is important to remember that despite geoengineering's appearance as a quick and easy fix to climate change, the process of reducing our dependence on fossil fuels is a difficult one. Given the sheer size of geoengineering projects there will be substantial costs in terms of political and physical capital (Starke et al., 2013: 325). However if used, alongside other technologies, it has the potential of helping us reach our carbon concentration goals by the end of century. Nevertheless, CDR on the scales as suggested by IPCC's climate scenarios are still "poorly understood and undeveloped" and some researchers claim there is little reason to believe they could be applied on global scales (Schlesinger, 2014). To conceptualize implementation there are a number of factors to consider such as: funding, governance, research, and impacts on agriculture and biodiversity (Ibid.). There are also issues of the launch and timing of CDR as well as problems related to other economic and environmental systems that will compete with CDR for land and resources (IPCC Fifth Assessment

Report, 2014: 433). Within this section, these questions will be addressed in terms of research, regulations, costs, and integration into our existing infrastructure.

**Approaches to Research**

The first concern with CDR and geoengineering in general is the small amount of research being conducted. The previous section discussed uncertainties and potential risks of CDR and these need to be understood as real problems. Public policy will ultimately be determined by our scientific understanding of CDR. Given that many geoengineering technologies are as of now only hypothetical and their impacts are not entirely clear, the importance of further research cannot be overstated (Ibid.: 484). Another important aspect of this research is that it allows us to get a clearer picture of costs and side-effects, acceptable or otherwise (Schlesinger, 2014). For many CDR technologies, the eventual implementation will depend on cost feasibilities, actual impacts on global warming, and compatibility with mitigation aims (IPCC Fifth Assessment Report, 2014: 489). With this in mind, the first step in any practical implementation of CDR is to focus on uncovering the unknown effects through research.

Leading geoengineering scientist David Keith has outlined one scenario by which SRM research could be conducted with relative safety. While CDR is different from SRM and does not present the same risks, many of the suggestions outlined could be applicable. The first step is theoretical research accompanied by lab work and modelling. Following this small-scale experimentations could take place to get better understanding of risks and means of improvement. If previous steps show minimal risk it could warrant small-scale implementation with the intention of finding adverse effects through additional experimentation and analysis of impacts. If these methods are proven to be beneficial, gradual deployment would follow. But even here, continuous research and impact assessment would be needed. (Keith, 2013: 80-86).

Given that CDR is a broad term which encompasses a large range of technologies some of these steps might not be useful for all. For ocean fertilization, where the scientific uncertainty is high and implementation could produce substantial harms, caution is warranted, even small scale experimentation in lakes or inland seas could disrupt ecosystems. On the other hand BECCS and direct air capture could conceivable be tested in desolate areas. Generally these type of research scenarios are a good guideline for the safe development of technologies with potentially large repercussions. For these and previously mentioned reasons future policies regarding CDR should include thorough research plans that allow for clearer pictures of risk, wherever it is humanly possible.

**Regulatory Mechanisms**

In regards to institutional structures, the challenge of creating international oversight for CDR usage still stands. The importance of international bodies is related to their ability to coordinate and contribute to the effectiveness of implementation. In regards to research, these institutions could conduct environmental monitoring and provide analysis of various effects (Young et al., 1997: 140). Generally these bodies could serve as a mechanism for course corrections to ensure that implemented solutions are as harmless and effective as possible. Furthermore, without some form of institutional support structure in place, it is difficult seeing CDR methods being developed quickly enough and on large enough scales to make a difference (Starke et al.,

2013: 325). Given the urgency of global warming and the need for action, international organizations could be used as a safety measure and facilitator (IPCC Fifth Assessment Report, 2014: 464). Another aspect requiring consideration is that of regulatory mechanisms. Environmental policies have historically lacked proper enforcement, as the networks and international communities that create these policies have not had policing or enforcement powers (Parsons, 1995: 516). One of the challenges for creating such powers will be creating it through "notions of 'co-operation' and 'negotiation'" instead of a top-down approach, something practically unfeasible in the multilateral world we live in (Ibid.: 517). For COP21 and climate conferences afterwards an agreed upon course of action needs to be set, one in which countries can feel comfortable enough to participate voluntarily. These type of challenges would also have to be addressed at lower instances of governance. Both national and local safety enforcement are key. Especially given that some CDR methods intend to store the captured carbon underground. For instance "potential problems like groundwater contamination or the sudden release of vast quantities of CO2 appear small but [are] by no means negligible" (Starke et al., 2013: 322). Given these threats, local laws and regulations need to ensure that risks are minimized and dangers are regularly tested.

A step to solving some of these issues could be to create global conventions or principles related to CDR and geoengineering. However crafting guidelines that can be agreed upon is not an easy task. Many existing frameworks raise questions regarding their meaning in terms of practical implementation and possible interpretations. Two examples of such principles are the 'Oxford Principles' and Robert Olson's criteria of 'Soft Geoengineering' (see Appendix A). Currently they could be seen as aspirational rather than clear policy outlines. Nevertheless they are a step in the right direction. Added to this is the importance of ensuring that CDR is not seen an alternative for conventional mitigation and adaptation (IPCC Fifth Assessment Report, 2014: 484). Even if principles might prevent harms from CDR implementation, the urgency of mitigation and emission cuts must not be lost in the message. Balance is needed. Not only could this create an ethical framework around CDR development and deployment but it could also streamline the agenda for future policies related to other areas.

Regardless of CDR deployment the largest challenge for the international community is the adherence to global emission and carbon concentration goals. This obstacle is at the core of solving global warming and CDR could either prove a hindrance or boon. Depending on external factors, CDR deployment in terms of size and timing might vary, many of the IPCC pathways show different scenarios in which we overshoot dangerous climate thresholds. In general, failures to curb emissions and tendencies of higher near-term emissions show heavier reliance on CDR in later parts of the century to ensure that climate goals are met (IPCC Fifth Assessment Report, 2014: 462). In this sense mitigation actions could impact the future usage of CDR and the amount needed. But given that CDR has the ability to generate negative emission flows, earlier implementation could delay drastic mitigation efforts to later parts of the century (Ibid.: 433). As such, when and how we use CDR could impact how overall mitigation trends form. While this could prove useful as a tool, allowing for emission convergence between developed and developing countries, it could also create delays in needed mitigation actions (Ibid.: 486).

Finally in regards to international frameworks, there could be clashes between CDR usage and existing carbon accountancy and emission curbing schemes. While not a major challenge, a

point that needs addressing nonetheless is how to view CDR in terms of contemporary carbon accountancy. Depending on the system in place, either a cap and trade system or other mechanisms for emission reductions, the question of how negative emissions are counted needs additional thinking. If CDR becomes commonplace, work on how to make it compatible with other existing frameworks is a must. We have to start thinking of ways of integrating CDR into national and international carbon plans.

**Costs of CDR**

Eventually the outcome of CDR effectiveness boils down to the scale of implementation and by extension its costs. Current estimations of the capital value associated with a full-fledged CDR industry has been guessed at "the scale of the entire fossil fuel industry" (Policy Exchange UK, 2013). Given that the fossil fuel industry is the world's largest, the notion of creating a new industry similar in size is a daunting thought. To get a sense of the sheer size of this venture, it is estimated that for direct air capture methods, getting rid of 100 ppm of $CO_2$ by the end of the century would require the building of 300 large industrial facilities each year for the remainder of the century (Ibid.). With many scientists already viewing CDR as an economics problem, making it viable is a necessity (Schlesinger, 2014). With current estimations of direct air capture costing $250-600 per ton of $CO_2$ there seems to be little incentive for companies to invest in these methods while alternatives like adding carbon capture to existing coal powered plants costs around $100 per ton (Ibid.). Over time the costs of CDR could fall with the emergence of economies of scale as expenses of research and fixed costs spread across an increasing number of CDR units. Some scientists have said that costs could fall as low as $30 per ton and that new processes are expensive at first (Ibid.). Outside startup costs there are also other feasibility issues, for instance with CDR methods aimed at storing liquefied carbon underground it is estimated that to compensate for 60 percent of the $CO_2$ produced by U.S. coal-fired plants annually, the liquid's volume would be close to the amount that the U.S. consumes in oil daily, around 20 million barrels (Starke et al., 2013: 323).

Another issue is that of available resources and land usage. While some CDR methods would require larger plots of land such as afforestation, it is conceivable that they could also be deployed on otherwise unused land. Direct air capture facilities could be put in desolate areas, similarly smaller air scrubbers and artificial trees could be placed alongside highways and a number of other locations. Afforestation could perhaps prove the most problematic as there is a direct question of scale vs. costs. While planting a tree is inexpensive as a tree's development is contingent on natural processes, the amount of trees needed to counteract emissions and act a carbon sink it might become impractical given competing needs for agriculture amongst other things. Here Klaus Lackner's artificial trees might be a viable solution, which studies have shown to be roughly 1000 times more efficient than actual trees at extracting carbon. Putting this into perspective, 10 million of these artificial trees could remove up to 3.6 billion tons of $CO_2$ or 10 percent of global annual emissions each year. In contrast you would need ten billion conventional trees to have the same effect (Vince, 2012). There is also the problem of BECCS, direct air capture, and conventional means of carbon capture using the same geological storage reservoirs. This could potentially limit their combined usage (IPCC Fifth Assessment Report, 2014: 485-486). The challenge here is to design CDR systems in which locations are efficiently utilized and provide the most benefit without

detracting from other sectors. This in itself might not be the largest challenge, which falls to funding, but it needs to be tackled nonetheless.

As previously mentioned the costs of CDR implementation are enormous, but given the urgency and seeming necessity of CDR, funding must be found. There are a number of potentially viable approaches to this problem. Firstly, governments could invest in basic and applied research. While there are common criticisms of governments 'picking winners' and 'disrupting free market mechanisms' it is important to note that the most impactful fields of the last century came into being due to early investments made by governments. For instance, the U.S. government made substantial investments into development of the Internet, and the fields of biotech and nanotech several decades before private actors got involved (Mazzucato, 2014). Additionally the benefits of this action are twofold, for starters it creates a knowledge base from which spinoff companies can further develop the field. This can be seen with spinoff companies often emerging from publically funded research labs during the early stages of tech industries. Secondly, given that a substantial amount of capital is needed in the early stages of development, by shifting this to governments it promises to foster a business climate in which venture capital is willing to invest in start-ups (Ibid.) Instead of investing in specific companies a policy that focuses on general research could create the foundations in which CDR ventures thrive.

There is also the question of who constitutes the demand base for CDR. Given that it is functionally a public good, clear incentives for the emergence of CDR are needed. Here there are several viable routes. For one, governments could directly commission CDR companies to provide them with negative emissions within the context of international carbon markets and goals. Another reason for this is that other emerging large-scale sectors are often driven by governments as the main consumers (Ibid.). A prominent example would be private space companies such as SpaceX, which would not be viable unless they had their current government contracts. In terms of scale and costs, such contracts are similar to the estimates of early CDR businesses. Alternatively, governments could use the emerging concept of 'social impact bonds', in which companies are paid for the successful delivery of a public good. Here companies could be paid for a certain amount of $CO_2$ removed from the atmosphere, creating direct incentives for the development of CDR businesses (Gov.uk, 2012). This approach also creates a focus on actual product delivery when signing contracts with private firms.

CDR would also have to be integrated into existing infrastructure. As CDR methods might compete with other areas for constrained resources, wherever possible, coordination and even compromises would be needed for positive outcomes for multiple parties. For instance, with BECCS and afforestation, the question of food vs. fuel (biomass) comes into play (IPCC Fifth Assessment Report, 2014: 433, 489). Of course creating new systems is difficult given pre-existing political and economic 'lock-ins'. There are however opportunities to forge linkages between emerging CDR companies and existing industries. Governments could increase incentives for other companies to seek CDR services by increasing taxes on emissions and highlighting CDR within existing carbon offsetting mechanisms, thereby placing many heavy polluters within the group of CDR consumers (Ibid.: 446). Furthermore, by fostering linkages between CDR businesses and adjacent industries it is possible to supply companies with early revenue streams. For example if CDR companies found ways to capture carbon at $200 per ton it would be cost effective for oil companies, who need large amounts of $CO_2$ for a cleaner oil production process known as

enhanced oil recovery, to buy $CO_2$ from them. Additionally $CO_2$ could be sold to 3rd generation algae-based biofuel producers who use it for growing biomass (Olson, 2012: 35). These are just some of the ways in which systems could be synchronized.

There is also the option of creating an international CDR fund or using the new Green Climate Fund for CDR development. The critical issue of the matter is ensuring that there are incentives for the emergence of a CDR industry as well as participation from all kinds of stakeholders. Inducement prize contests or 'incentive competitions' could work here. The basic premise is that a large cash sum is given to the entity able to reach a certain goal. This reward then incentivizes hundreds of projects of varying sizes to compete for it. What is noteworthy here is that only the winner is paid while simultaneously calling a vast number of self-funded actors into action. Some benefits include; vastly different approaches to problems, essentially fostering a growth spurt of innovation, creation of spinoff companies from viable projects aside from the winner, and spreading awareness of issues to the public and potential investors (Diamandis and Kotler, 2012). Some examples include the Orteig Prize which prompted Lindbergh's historic flight over the Atlantic, the Ansari X PRIZE which gave birth to the space tourism industry, and the Wendy Schmidt Oil Cleanup X Challenge in which the winners managed to increase the industry standard oil recovery efficiency threefold (Ibid). What is noteworthy is that many of the more innovative and efficient solutions do not come from established companies but small scale start-ups, something commonly ignored within conventional government contract schemes (Ibid). Despite the existence of the Virgin Earth Challenge (and the results of which remain to be seen), it does not preclude the creation of another CDR competition perhaps with more specific goals, larger public awareness, and a bigger cash prize funded by governments or international body. In fighting global warming, techniques used to reduce carbon emissions should be encouraged and rightfully rewarded.

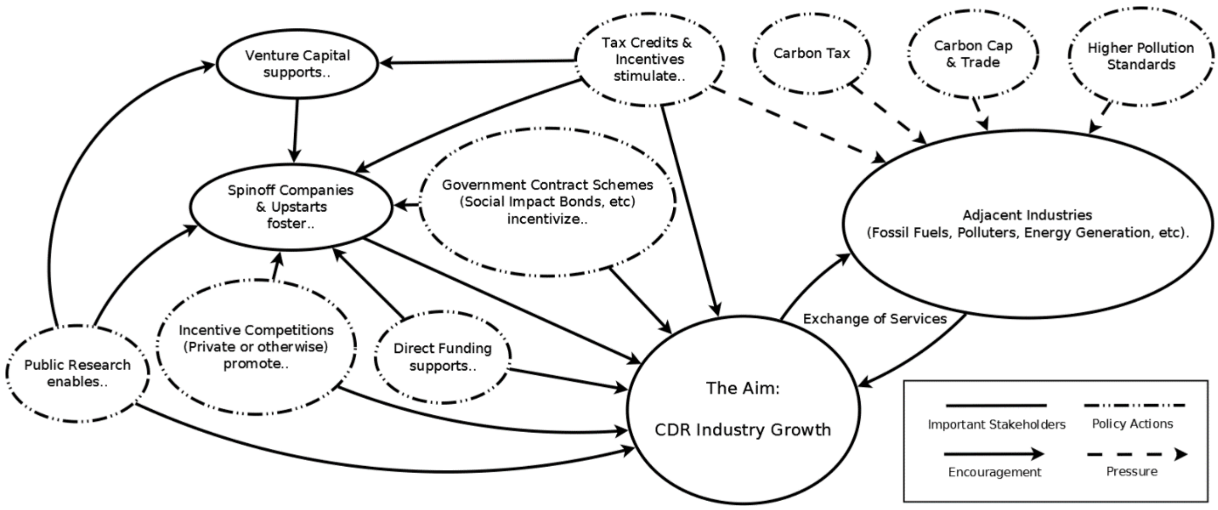



Figure 3: CDR policy influence map. Source: Self-produced

In general many of these opportunities lie within the overlap of the private and public sectors. As summarized in figure 3, despite complexity within the future governance of CDR and the web of related services in the periphery, if properly connected, public-private partnership offers the potential of delivering CDR on a significant scale and within cost effective prices (Parsons, 1995: 497). However for these linkages to emerge, there need to be strong actors who are capable of

acting as intermediaries. A convergence of objectives, interdependence, and coordination between various stakeholders is a must (Ibid.: 497-498). In the end these type of linkages could cut costs, spread knowledge, and increase the impact of CDR. With that in mind, they are at the very least worth exploring.

## Discussion and Conclusion

The use of geoengineering is not preferable, in an ideal world preventive measures against global warming would have taken place decades ago. But we do not live in an ideal world and studies have shown impending dangers if we do not act. Given the complexities and past failures of creating international climate accords, one might cast doubt on the success of COP21 in Paris and the policies that follow. Regardless of whether the world agrees upon a universal and binding climate agreement, the road ahead will be difficult. The developing world is uplifting billions of people to higher standards of living and with that comes higher emissions. At the same time industrialized countries have not managed to cut enough emissions to make a significant impact on global rates. In this the IPCC has stated several times that CDR technologies, in particular BECCS and afforestation, will be needed for the most optimal climate outcomes. Given our predicament and without considering radical alternatives, there is little doubt that CDR will be needed. CDR could mean the difference between a world where some regions win or lose out due to a 2ºC global increase and a world in which ecosystems are destroyed, where billions of lives are endangered, and a place where international relations are beyond recognition. If CDR holds promise of combating global warming, it must be explored. However in this exploration, safeguards need to be established. We need to remove the ethical and practical uncertainties surrounding the technologies.

When pursuing technologies which have the potential of changing the world, it is important to ensure that negative effects are minimized and reduced to acceptable levels. More fundamentally, we also need to make sure that CDR is actually the solution some make it out to be. Given its current state as an underdeveloped, complex, and costly venture a lot remains to be done before it can create a real dent in global $CO_2$ emissions. Another deciding factor is whether CDR requires governance in the form of international accords that have previously failed. The answer is not clear. In some cases, CDR permits itself to frameworks that entail coordination rather than governance. Giving it an edge over other forms of geoengineering. But regarding scientific uncertainty and potential negative effects, stricter international regimes might still be needed.

Overall, the path to making CDR viable rests within additional research, common guidelines for risk management, and cooperation in areas where it's needed. Additionally given the enormous costs associated with CDR, there is need for incentives to foster the emergence of a CDR industry. Whether this entails incentive competitions, government schemes, pressure on private actors, or international funding remains to be seen. But given the sheer size of a needed CDR industry, no stone should be left unturned in the pursuit of its financing.

In the end, as long as political and social participants can understand CDR not as a contingency plan nor an alternative to emission cuts but as a complementary tool in our fight against global warming it might bring significant benefits. However if misused under a lens of over-optimism and techno-optimism, it could hinder optimal outcomes. Given that the future will

require cuts in emissions regardless of whether people and firms are ready for them, demand international cooperation like never before, and call for convergence of industrialized and developing countries alike while also taking into account growing concentrations of $CO_2$, we have passed the point where we have the luxury of looking at alternative ways of thinking and social structures. As it stands CDR might be a necessity, one that desperately needs to find its place within the complex frameworks that make up global environmental policies. With diligent research, careful planning, adequate funding, and bold political action it might become the savior we need.

# References


Beder, S. (2006). *Environmental principles and policies*. London: Earthscan.

Collingridge, D. (1980). *The social control of technology*. New York: St. Martin's Press.

Cox, Peter M. et al. (2000). Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature, 408(6809), pp.184-187.

Diamandis, P. and Kotler, S. (2012). Abundance. New York: Free Press.

Doyle, A. (2012). *Fertilizing oceans with iron dust helps sink carbon: study*. [online] Uk.reuters.com. Available at: http://uk.reuters.com/article/2012/07/20/us-climate-oceans-idUSBRE86J1E920120720 [Accessed 26 Dec. 2014].

Foster, John. (2015). After Sustainability. New York: Routledge.

Foster, John. et al. (1997). Valuing nature?. London: Routledge.

Frölicher, Thomas Lukas. et al. (2013). Continued global warming after CO2 emissions stoppage. Nature Climate change, 4(1), pp.40-44.

Global Carbon Project, (2014). *CO2 emissions set to reach new 40 billion tonne record high in 2014 | Tyndall Centre for Climate Change Research*. [online] Available at: http://www.tyndall.ac.uk/communication/news-archive/2014/co2-emissions-set-reach-new-40-billion-tonne-record-high-2014-0 [Accessed 27 Dec. 2014].

Gov.uk, (2012). *Social impact bonds - Detailed guidance - GOV.UK*. [online] Available at: https://www.gov.uk/social-impact-bonds [Accessed 28 Dec. 2014].

Green Climate Fund, (2014). *Total pledges nearing USD 10.2 billion*. [online] Available at: http://news.gcfund.org/wp-content/uploads/2014/12/release_GCF_2014_12_10_austria_pledge.pdf [Accessed 29 Dec. 2014].

Holder, J. (2004). *Environmental assessment*. Oxford: Oxford University Press.

Hoven, J. et al., (2014). *Responsible innovation 1*. Springer Netherlands.

Hulme, M. (2014). *Can science fix climate change?*. Polity Press.

IPCC Fifth Assessment Report. (2014). IPCC Assessment Report. [online] United Nations Intergovernmental Panel on Climate Change. Available at: http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_ALL_FINAL.pdf [Accessed 26 Dec. 2014].

IPCC Fourth Assessment Report. (2007). IPCC Assessment Report. [online] United Nations Intergovernmental Panel on Climate Change. Available at: http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_full_report.pdf [Accessed 19 Dec. 2014].

Keith, D. (2013). *A case for climate engineering*. MIT Press.

Kiehl, J. and Trenberth, K. (1997). *Earth's Annual Global Mean Energy Budget*. [online] National Center for Atmospheric Research. Available at: http://web.archive.org/web/20060330013311/http:/www.atmo.arizona.edu/students/courselinks/spring04/atmo451b/pdf/RadiationBudget.pdf [Accessed 27 Dec. 2014].

Lynas, M. (2008). *Six degrees*. Washington, D.C.: National Geographic.

Lynas, M. (2011). *The god species*. Washington, D.C.: National Geographic.

Marshall, M. (2011). *Political backlash to geoengineering begins*. [online] Newscientist.com. Available at: http://www.newscientist.com/article/dn20996-political-backlash-to-geoengineering-begins.html [Accessed 26 Mar. 2015].

Mazzucato, M. (2014). The entrepreneurial state. Revised ed. London: Anthem Press.

NASA, (n.d.). *Global Climate Change: Effects*. [online] Climate Change: Vital Signs of the Planet. Available at: http://climate.nasa.gov/effects/ [Accessed 25 Dec. 2014].

National Climatic Data Center, (2014). *Global Analysis - October 2014 | State of the Climate | National Climatic Data Center (NCDC)*. [online] Ncdc.noaa.gov. Available at: http://www.ncdc.noaa.gov/sotc/global/2014/10 [Accessed 27 Dec. 2014].

OECD, (2012). OECD Environmental Outlook to 2050.

Olson, R. (2012). Soft Geoengineering: A Gentler Approach to Addressing Climate Change. *Environment: Science and Policy for Sustainable Development*, 54(5), pp.29-39.

Oxford Geoengineering Programme, (n.d.). *Oxford Geoengineering Programme*. [online] Geoengineering.ox.ac.uk. Available at: http://www.geoengineering.ox.ac.uk [Accessed 21 Nov. 2014].

Parsons, D. (1995). *Public policy*. Aldershot, UK: Edward Elgar.

Policy Exchange UK, (2013). *Is there a role for Negative Emissions Technologies in tackling climate change?*. [video] Available at: http://youtu.be/G4EHLleWk-s [Accessed 29 Dec. 2014].

Renforth, P. (2012). The potential of enhanced weathering in the UK. *International Journal of*

*Greenhouse Gas Control*, 10, pp.229-243.

Ringland, G. (2002). *Scenarios in public policy*. Chichester: Wiley.

Sample, I. (2005). *Warming hits 'tipping point'*. [online] The Guardian. Available at: http://www.theguardian.com/environment/2005/aug/11/science.climatechange1 [Accessed 25 Mar. 2015].

Schlesinger, V. (2014). *Can carbon dioxide removal save the planet? | Al Jazeera America*. [online] America.aljazeera.com. Available at: http://america.aljazeera.com/articles/2014/4/12/can-carbon-dioxideremovalsavetheplanet.html [Accessed 26 Dec. 2014].

Schwarz, M. and Thompson, M. (1990). *Divided we stand*. Hemel Hempstead: Harvester Wheatsheaf.

Starke, L. et al. (2013). *State of the world 2013*. Worldwatch Institute.

Thomas, Chris D. et al. (2004). Extinction risk from climate change. *Nature*, 427(6970), pp.145-148.

UNFCCC, (2014). *Lima call for climate action*. Lima: United Nations Framework Convention on Climate Change.

van Vuuren, D. et al., (2011). The representative concentration pathways: an overview. [online] Available at: http://download.springer.com/static/pdf/740/art%253A10.1007%252Fs10584-011-0148-z.pdf?auth66=1421346147_d84bdfd1be9988abe207c97e0ec3bc17&ext=.pdf [Accessed 29 Dec. 2014].

Vince, G. (2012). *Sucking CO2 from the skies with artificial trees*. [online] BBC Future. Available at: http://www.bbc.com/future/story/20121004-fake-trees-to-clean-the-skies [Accessed 6 Dec. 2014].

Virgin Earth Challenge, (n.d.). *Virgin Earth Challenge*. [online] Virginearth.com. Available at: http://www.virginearth.com/ [Accessed 26 Nov. 2014].

Wigley, T. (1983). The pre-industrial carbon dioxide level. *Climatic Change*, 5(4), pp.315-320.

Young, O. et al., (1997). *Global Governance: Drawing Insights from the Environmental Experience*. Cambridge, Massachusetts: MIT Press.

## Appendix A

| Oxford Principles |
|---|
| 1. Geoengineering to be regulated as a public good.<br>2. Public participation in geoengineering decision-making<br>3. Disclosure of geoengineering research and open publication of results<br>4. Independent assessment of impacts<br>5. Governance before deployment |
| **Soft Geoengineering** |
| 1. Can be applied locally<br>2. Scalable to larger areas<br>3. Low or no anticipated negative impacts on ecosystems or society<br>4. Rapid reversibility if problems do arise<br>5. Has multiple benefits, beyond impacts on climate<br>6. Analogous to natural processes<br>7. Effects are large enough, soon enough to be worthwhile<br>8. Cost-effective with mature technologies deployed at moderate scale |

Sources: Oxford Geoengineering Programme & Olson, 2012