Reframing the Climate Change Problem: Evaluating the Political, Technological, and Ethical Management of Carbon Dioxide Emissions in the United States

by

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ABSTRACT

Research confirms that climate change is primarily due to the influx of greenhouse gases from the anthropogenic burning of fossil fuels for energy. Carbon dioxide (CO_2) is the dominant greenhouse gas contributing to climate change. Although research also confirms that negative emission technologies (NETs) are necessary to stay within 1.5-2°C of global warming, this dissertation proposes that the climate change problem has been ineffectively communicated to suggest that CO_2 emissions reduction is the only solution to climate change. Chapter 1 explains that current United States (US) policies focus heavily on reducing CO_2 emissions, but ignore the concentrations of previous CO_2 emissions accumulating in the atmosphere. Through political, technological, and ethical lenses, this dissertation evaluates whether the management process of CO_2 emissions and concentrations in the US today can effectively combat climate change.

Chapter 2 discusses the historical management of US air pollution, why CO_2 is regulated as an air pollutant, and how the current political framing of climate change as an air pollution problem promotes the use of market-based solutions to reduce emissions but ignores CO_2 concentrations. Chapter 3 argues for the need to reframe climate change solutions to include reducing CO_2 concentrations along with emissions. It presents the scientific reasoning and technological needs for reducing CO_2 concentrations, why direct air capture (DAC) is the most effective NET to do so, and existing regulatory systems that can inform future CO_2 removal policy. Chapter 4 explores whether Responsible Innovation (RI), a framework that includes society in the innovation process of emerging technologies, is effective for the ethical research and deployment of DAC; reveals the need for increased DAC governance strategies, and suggests how RI can be expanded to allow continued research of controversial emerging technologies in case of a climate change emergency. Overall, this dissertation argues that climate change must be reframed as a two-part problem: preventing new CO_2 emissions and reducing concentrations, which demands increased investment in DAC research, development, and deployment. However, without a national or global governance strategy for DAC, it will remain difficult to include CO_2 concentration reduction as an essential piece to the climate change solution.

DEDICATION

This dissertation is dedicated to my mother Stephanie H. Morton, the first Dr. Morton.

Thank you, mom, for inspiring me to be the second.

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TABLE OF CONTENTS

CHAPTER Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

A SCIENTIFIC SUMMARY OF THE CLIMATE CHANGE PROBLEM

International, extensively vetted research efforts for at least three decades have confirmed that climate change is primarily due to the influx of greenhouse gases created from the anthropogenic activities of burning coal, oil, and gas for energy (USGCRP 2018). Carbon dioxide (CO_2) is the dominant greenhouse gas contributing to climate change. Although it has been known for almost 200 years that greenhouse gases trap heat (USGCRP 2018; Fourier 1824), fossil fuels continue to be used at ever increasing rates. As a consequence, the United States (US) average temperature has increased by 1.8°F since 1901 (USGCRP 2018). This increase in temperature has led to more extreme heat events, increased nighttime temperatures, precipitation downpours, increased flooding, increased ocean temperatures, sea level rise, and thawing of permafrost (USGCRP 2018; 2017; Rogelj et al. 2018). All of these changes have societal consequences for health, water supply, agriculture, and transportation. They also have shown to greatly impact the economy.

The global CO_2 concentration was at 278 ± 2 ppm in 1750, just before the industrial revolution (Etheridge et al. 1996). It has since increased by about 48% with a December 2019 global mean reading of 412.02 ppm (National Oceanic and Atmospheric Administration 2020b). The increase has been by 0.93-3.01 ppm every year over the past 20 years (USGCRP 2017). Figure 1 shows the annual increase of CO_2 concentration as measured by the National Oceanic and Atmospheric Administration (NOAA) at Mauna Loa Observatory in Hawaii (National Oceanic and Atmospheric Administration 2020a). The change in CO_2 concentration is large. The exponential fit added to data from NOAA suggests an annual increase in the rate of CO_2 emissions by 2% per year. During the ice ages of the last million years CO_2 concentrations moved back and forth between 180 ppm and 280 ppm. A level of concentration as high as today was last experienced about 3 million years ago and resulted in a much higher global temperature and a sea level much higher than today (USGCRP 2017).

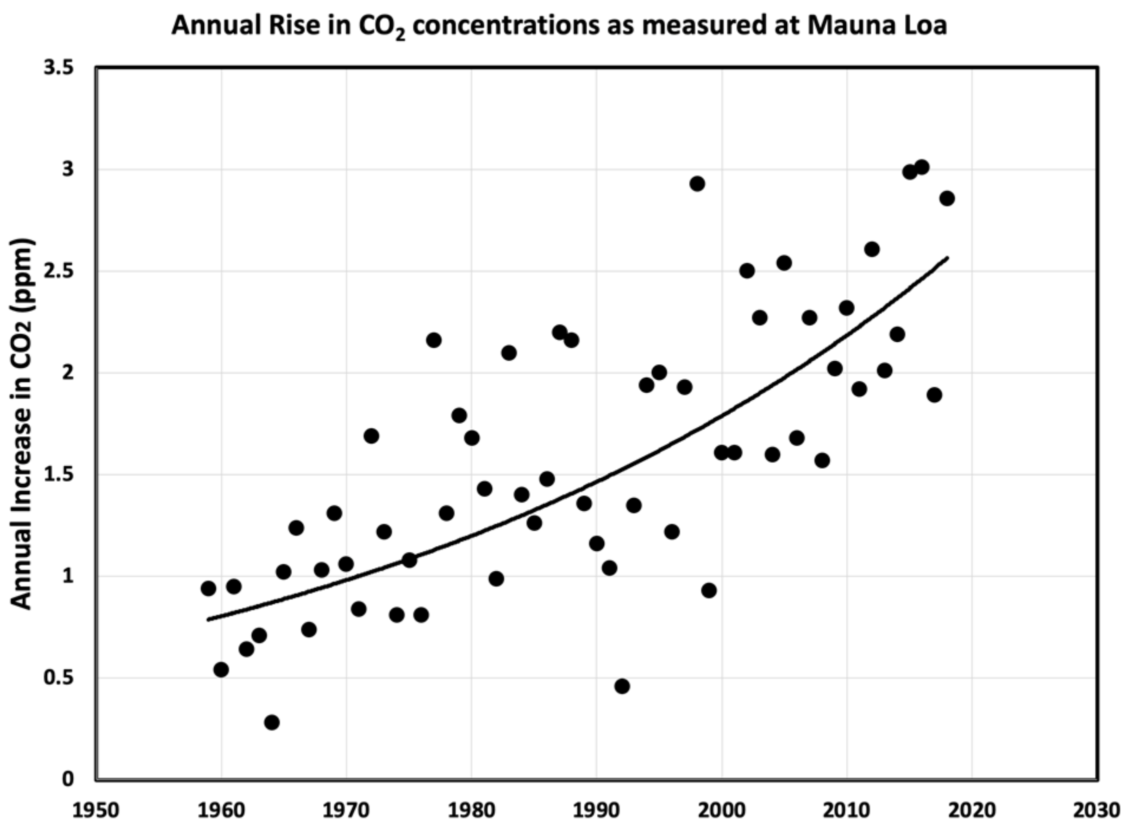

Figure 1. Annual Rise in CO_2 Measured at Mauna Loa, Hawaii (Data compiled by NOAA, figure by Klaus S. Lackner)

In response to these dramatic changes and the predicted deleterious consequences of such changes, researchers and governments have called for better management of CO_2 emissions. International negotiations have set a goal to keep greenhouse gas emissions low enough to stay below 2°C of warming from preindustrial temperatures (UNFCCC

2019a). Recent studies show that this cannot be done without the use of carbon dioxide removal (IPCC 2018). The Intergovernmental Panel on Climate Change (IPCC) defines carbon dioxide removal (CDR) as “anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products” (J. B. R. Matthews et al. 2018). CDR is integral to achieving net zero emissions by balancing the amount of CO_2 emitted into the atmosphere with the amount of CO_2 being removed, also known as carbon neutrality.

The conversation surrounding 2°C warming began in the 1970’s when economist William Nordhaus wrote about the dangers of the doubling or more of CO_2 concentrations in the atmosphere which was then predicted to lead to around 2°C of warming. Nordhaus emphasized that these numbers at the time were just a rough guess (Nordhaus 1975). Around the same time, a 1977 report published by the National Academy of Sciences revealed that the natural decline of CO_2 concentrations in the atmosphere would take centuries. The report therefore questioned whether the US should continue relying on fossil fuels as its primary energy source or begin investing in research to produce alternative energy sources (National Research Council 1977). This research concluded that immediate reduction of CO_2 emissions would be necessary to manage climate change. CDR was also mentioned, but its research was in the very early stages and therefore not considered a reliable strategy (National Research Council 1977).

Research by the Stockholm Environment Institute in 1990 later confirmed the work of Nordhaus when creating specific targets to mitigate climate change. The report gives an upper target of 2°C maximum temperature increase “beyond which the risks of grave damage to ecosystems, and of non-linear responses, are expected to increase rapidly" (Rijsberman and Swart 1990). The report also gives a lower level target of 1°C maximum temperature increase which was most likely unavoidable due to greenhouse gases already in the atmosphere, however, "temperature increases beyond 1.0°C may elicit rapid, unpredictable, and non-linear responses that could lead to extensive ecosystem damage" (Rijsberman and Swart 1990). It is worth noting that data collection on a global scale has shown that greenhouse gases from human activity has already caused ~1°C of warming above preindustrial temperatures (IPCC 2018).

The United Nations Framework Convention on Climate Change (UNFCCC) (United Nations 1992) was created in 1992 to achieve "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." However, the 2°C warming limit did not enter into political negotiations until 1996 when the European Council of Environment agreed that "global average temperatures should not exceed 2°C above pre-industrial level and that therefore concentration levels lower than 550 ppm CO_2 should guide global limitation and reduction efforts" (European Commission 1996). This decisions was based off of findings from the United Nation's Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (IPCC 1995).

The IPCC was created in 1988 by the World Meteorological Organization and the United Nations Environment Programme to "provide policymakers with regular scientific assessments on the current state of knowledge about climate change" (IPCC 2020). Its First Assessment Report published in 1990, discussing the need for global cooperation to combat climate change, was a major reason why the UNFCCC was created. Since then, the IPCC has published several research reports upon the request of the UNFCCC (IPCC 2020).

The UNFCCC later operationalized their mission through the Kyoto Protocol in 1997 at the Conference of the Parties in Kyoto, Japan. The agreement required industrialized countries to reduce their greenhouse gas emissions and achieve "an average 5 per cent emission reduction compared to 1990 levels over the five year period 2008–2012" (UNFCCC 2019b). However it was not until 2010 at the 16th Conference of the Parties held in Cancun, Mexico where the parties agreed to "a maximum [global] temperature rise of 2 degrees Celsius above pre-industrial levels, and to consider lowering that maximum to 1.5 degrees in the near future" (UNFCCC 2010).

Based on the IPCC's Fifth Assessment Report (IPCC 2013), the 2°C threshold is likely well below 550 ppm. In part, this discussion is complicated by the fact that the relationship between CO_2 concentration in the atmosphere and expected global warming is itself subject to uncertainties. On the one hand, the Fifth Assessment Report states clearly that for the probability of 2°C warming to remain low, the greenhouse gas concentration in the atmosphere must remain below 450 ppm. The report emphasizes that this is the effective concentration of CO_2, which includes CO_2 and other greenhouse gases whose concentration is converted into CO_2 equivalence. On this basis, the greenhouse gas concentration in the atmosphere has already crossed the 450 ppm_e threshold. Therefore, the probability of avoiding 2°C warming is low. The Fifth Assessment Report was also the first IPCC report to assess CDR as a climate change mitigation strategy. The report shows several mitigation scenarios where CDR plays an important role in stabilizing CO_2 atmospheric concentrations for staying below 2°C warming when reducing fossil fuel use is not enough or is too expensive (IPCC 2013).

Five years after the UNFCCC committed to staying below 2°C warming and two years after the Fifth Assessment Report was published, the UNFCCC finally put their commitment into action in 2015 under the Paris Agreement. This agreement requires each party to create Nationally Determined Contributions that state what measures they will take to stay below 2°of global warming which will be evaluated and updated every five years (UNFCCC 2019a).

In 2018, the IPCC published a special report showing the dangers of increasing to 1.5°C or 2°C above preindustrial temperatures. Even though staying at 1.5°C will cause fewer extreme changes than increasing to 2°C, both temperatures will create dangerous effects including extreme heat, heavy precipitation, drought, precipitation shortages, melting ice sheets, and sea level rise. These severe changes will increase risks to human health, food and water security, and to economic growth (IPCC 2018).

Adaptation needs will be lower at 1.5°C and become more challenging if temperatures increase to 2°C. Staying at 1.5°C will help to prevent thawing of permafrost which could release more CO_2 into the atmosphere. However, vulnerable areas such as small islands and developing countries will already be experiencing various climate related effects at 1.5°C (IPCC 2018). The IPCC and the US Global Change Research Program reports agree that staying below 2° C of global warming requires a drastic decline of CO_2 emissions reaching net zero by 2050 (USGCRP 2017; 2018; Rogelj et al. 2018). Furthermore, staying at 1.5°C will require CO_2 reductions in all sectors at unprecedented scales and the use of CDR will be essential (IPCC 2018).

Since the industrial revolution, about 42% of anthropogenic CO_2 emissions remain in the atmosphere. The rest of those emissions are taken up by land and ocean sinks through the natural carbon cycle (Le Quéré et al. 2016). However, as anthropogenic emissions increase, the natural uptake of emissions begins to decrease (Hoegh-Guldberg et al. 2018). Therefore, about half of all CO_2 emissions ever emitted will remain in the atmosphere for hundreds of years (K. S. Lackner et al. 2012; Prentice et al. 2001). Because at least some part of CO_2 emissions persists in the atmosphere for very long times, emissions must be balanced by CDR if the CO_2 concentration is to be controlled. If a reduction in the use of fossil fuels, carbon capture and storage at point source, and CDR come together to eliminate or cancel out all emissions, the world economy can achieve carbon neutrality and the CO_2 concentration in the atmosphere will very gradually drop because of natural processes. If one includes these in the total balance, then at the carbon neutral point the CO_2 in the atmosphere is stabilized.

However, even if carbon neutrality is achieved, many studies show that climate change effects will persist (Gillett et al. 2011; MacDougall, Eby, and Weaver 2013; H. D. Matthews and Zickfeld 2012; Solomon et al. 2009; Eby et al. 2009). A study by Solomon et al shows that even if emissions were to stop completely, climate change effects such as sea level rise, rainfall reductions, and extreme heat will continue for at least 1,000 years (Solomon et al. 2009). Therefore, more must be done than only eliminating or canceling out CO_2 emissions. Reports from the IPCC and the US Global Change Research Program point out that staying at 1.5°C warming also requires CDR to achieve net negative emissions. CDR does this using negative emission technologies (NETs) to remove more

CO_2 from the atmosphere than is emitted followed by permanent storage geologically, terrestrially, in oceans, or in products (USGCRP 2017; 2018; Rogelj et al. 2018).

Thus, NETs have been considered for two different tasks, the first is to deal with the residual emissions that are difficult to eliminate by other means. The second is to create net negative emissions and drive CO_2 concentrations in the atmosphere back down to 450 ppm or lower. Some studies limit themselves to the former. For example, the National Academies of Sciences, Engineering, and Medicine study on negative emissions explicitly focuses using NETs for reducing emissions and leaves out the possibility of scaling the technology to the point that it would create net negative emissions (National Academies of Sciences, Engineering, and Medicine 2019). On the other hand, the IPCC in its report clearly states a need for net negative emissions in most scenarios to limit temperature rise to 1.5°C (IPCC 2018).

The mission of the UNFCCC discusses the need to minimize “threats of serious or irreversible damage” from climate change (United Nations 1992; Solomon et al. 2009). This includes accounting for “all relevant sources, sinks and reservoirs of greenhouse gases and adaptation” (United Nations 1992). The UNFCCC defines a sink as “any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere” (United Nations 1992). By this definition, the UNFCCC also supports NETs and CDR. Although the aforementioned reports and the UNFCCC have explicitly shown the need for NETs, policies in the US and globally are doing very little to incorporate these technologies within their climate change mitigation portfolios (Peters and Geden 2017; Kriegler et al. 2013). For example, besides using afforestation and reforestation to reach carbon neutrality, none of the parties involved in the Paris Agreement have mentioned NETs in their Nationally Determined Contributions to achieve net negative emissions (Peters and Geden 2017; UNFCCC 2016).

It is difficult to advance the cause of NETs due to the sheer scale of the climate change problem. It will take a very large-scale effort to transition away from avoiding or reducing emissions to an approach which is focused on reducing the CO_2 concentration in the atmosphere. For example, the entire discussion of the UNFCCC has been in terms of allowed emissions rates and the need to reduce emissions. Furthermore, the 2007 US Supreme Court case, Massachusetts v. Environmental Protection Agency, ruled that CO_2 should be defined as an air pollutant under the Clean Air Act (Massachusetts v. Environmental Protection Agency 2007). Implicit in this discussion is that there are polluters who produce emissions and the size of these emissions must be reduced. Even in the best of circumstances emissions will gradually reduce to zero. To the extent that the carbon once mobilized remains in the environment, an approach of emissions reductions by itself cannot fix CO_2 concentrations that already exceed the allowable limit.

This framing of climate change as a pollution problem suggests that CO_2 emissions mitigation is the only measure necessary to defeat climate change. Recent US policies like the Clean Power Plan and the Affordable Clean Energy rule focus heavily on reducing CO_2 emissions (US EPA 2015b; 2019b), but ignore the atmospheric concentrations of previous CO_2 emissions that continue to sit in the atmosphere for hundreds to thousands of years (K. S. Lackner et al. 2012; US EPA 2015c). While NETs are used in conjunction with other CO_2 mitigation strategies to achieve carbon neutrality, NETs are the only solution for reducing CO_2 concentrations.

Current policies have failed to address that climate change is a two-part problem: (1) preventing new CO_2 emissions and (2) reducing concentrations in the atmosphere. While in the 1970's it may have been possible to stay below 2°C warming by only significantly reducing emissions, today that is no longer the case. Framing the climate change problem solely as one of curbing pollution has led the US to solutions that can slow down emissions but end up ignoring CO_2 concentrations -- even if they reach dangerous levels. For example, the IPCC Fifth Assessment Report states that staying within 2°C warming requires "cumulative CO_2 emissions from all anthropogenic sources since 1870 to remain below about 2900 $GtCO_2$" (IPCC 2014). About two thirds of this amount (1900 $GtCO_2$) was already emitted by 2011 (IPCC 2014). Furthermore, the most recent monitoring shows that CO_2 atmospheric concentrations in 2020 are at about 412.30 ppm (National Oceanic and Atmospheric Administration 2020b). While it is difficult to determine the exact concentration of CO_2 that will maintain an average 1.5-2°C rise in global temperature, research suggests that current levels have likely surpassed that limit or will surpass it in the next few years (IPCC 2013; 2018). Curbing more emissions will not bring that concentration down.

If one were to focus on meeting CO_2 concentration targets or thresholds rather than emission rates, the world would have to consider a finite CO_2 budget for atmospheric levels. If that budget is exceeded (i.e. in overdraft), the only logical approach is to remove that excess. This is simply a scientific observation. How that removal could be done is also a scientific question; how it ought to be done is a political and ethical question. No matter how it is done, the process will be gradual, and the impacts will be distributed among different countries and across many generations. One way or another, if an overdraft occurs, fixing the problem would mean that societies would need to remove a sufficient amount of CO_2 from the system. That is the meaning of "negative emissions." These differ from emissions reductions, which means reducing or preventing new emissions from reaching the atmosphere to begin with. In practical terms, firms that are in the business of creating negative emissions (taking CO_2 out of the atmosphere) may not be the same firms that are trying to slow down the amount of emissions they are producing.

Although the Kyoto Protocol and the Paris Agreement have determined global goals to reduce greenhouse gas emissions for maintaining global warming under 2°C, neither of these agreements provide a governance approach to reducing CO_2 concentrations. They are focused solely on emissions reductions. By now, it should be self-evident that this approach only deals with half of the climate change problem because, since atmospheric concentrations are already exceeding the levels requires by the 2°C limit, it is also necessary to reduce the CO_2 concentration in the atmosphere.

Reaching consensus among all sovereign countries has been extremely difficult (Sunstein 2007; Hermwille et al. 2017; Kuyper, Schroeder, and Linnér 2018), just for emissions reduction. Even though the US at the time was the largest CO_2 emitter in the world, it never ratified the Kyoto Protocol, which aimed to create emission targets for all developed countries (Sunstein 2007). Worldwide, the Kyoto Protocol did little to reduce emissions (Sunstein 2007). While a signatory to the Paris Agreement in 2015, the US is now scheduled to withdraw (Shear 2017), even though the ground-up and flexible approach of the agreement allows individual countries to create their own pathways toward staying below 2°C instead of following a prescribed method (UNFCCC 2019a). It is not just the US that has difficulties in committing to an emissions pathway that meets the 2°C limit. Adding up all the party commitments made will still result in a trajectory that will push warming well above the 2°C ceiling (UNFCCC 2016). However, since the Paris Agreement allows all countries to follow their individual paths, the focus of this research is on the US with its own unique challenges.

Even though climate change is caused by a wide range of greenhouse gases, CO_2 is and should continue to be a focus of attention due to the abundance of CO_2 emissions produced in the US when compared to other greenhouse gases. In 2017, CO_2 made up ~82% of all greenhouse gas emissions in the US, followed by methane (CO_2 equivalent) at ~10%, nitrous oxide (CO_2 equivalent) at ~6%, and fluorinated gases (CO_2 equivalent) at ~3% (US EPA 2017). These percentage are based on the global warming potentials of the various greenhouse gases, which takes into account their ability to absorb infrared radiation and their lifetime in the atmosphere. Table 1 shows the atmospheric lifetimes and percentages of the six dominant well-mixed greenhouse gases contributing to climate change.

Table 1. Atmospheric Lifetimes of Well-mixed Greenhouse Gases

Name	**Atmospheric Lifetime**	**Percent of all GHG emissions in 2017 (CO_{2e})**	**Source**
Carbon Dioxide	100-1000+ years	~82%	(US EPA 2015c)
Methane	12.4 years	~10%	(Stocker 2014)
Nitrous Oxide	121 years	~6%	
Hydrofluorocarbons	2.1 days-42 years	~3%	
Perfluorocarbons	1.1 days-50,000 years		
Sulfur Hexafluoride	3,200 years		

While many of these gases have substantial atmospheric lifetimes, the amount of CO_2 produced yearly makes CO_2 by far the largest contributor to the increasing radiative forcing than the other greenhouse gases. Compared to methane and hydrofluorocarbons it has a much longer residence time in the atmosphere, rendering CO_2 emissions far more difficult to reverse. Between 2005 and 2011, CO_2 contributed to 80% of the increase in global radiative forcing and has been the dominant greenhouse gas affecting this increase from 1998 to 2013 (Stocker 2014). Therefore, the combination of CO_2 atmospheric lifetime, its abundance in the atmosphere compared to other greenhouse gas emissions, and its large contribution to radiative forcing shows the necessity to focus specifically on managing CO_2 emissions and concentrations for combating climate change. Because of the importance of CO_2, this research is focused on this single greenhouse gas. Limiting the focus to CO_2 makes it possible to consider the climate change problem a carbon problem and measure the impact essentially by the amount of fossil carbon extracted from the ground.

When explored through political, technological, and ethical lenses, can the current management process in the US effectively manage CO_2 to combat climate change? Based on this analysis, current approaches alone will not. The historical management of air pollution in the US, why the US chose to regulate CO_2 as an air pollutant, and how the political framing of climate change as an air pollution problem has led to the increased use of market-based solutions, (i.e. management of CO_2 that focuses on emission trading and other methods like carbon taxes that aim to reduce emissions) suggests that the answer is no. The current approach ignores CO_2 concentrations in the atmosphere, leaving that part of the problem untouched. As already argued, scientific evidence leads to a framing of climate change mitigation strategies as reducing CO_2 concentrations *as well as* reducing emissions. Given the state of research and political debate about reducing concentrations through NETs, it is important to go beyond the scientific and policy approaches to consider the ethics of such efforts. Responsible Innovation is a relatively recent idea and framework for examining the ethical deployment of emerging technologies, and its relevance to direct air capture technologies had not previously been tested but shows that gaps in governance can make ethical research and deployment more challenging. If managing climate change means a need to reduce CO_2 concentrations, which requires increased investments in direct air capture technology and a way to increase deployment of direct air capture in an ethical manner, then the US is currently not prepared.

CHAPTER 2

POLITICAL FRAMING AND ITS EFFECT ON MANAGING AIR POLLUTION IN THE UNITED STATES

Introduction

The United States (US) has come a long way in reducing air pollution starting with the Air Pollution Control Act of 1955. However, carbon dioxide (CO_2), along with other greenhouse gases, has only been defined as an air pollutant since the Massachusetts v. Environmental Protection Agency Supreme Court case in 2007 (Massachusetts v. Environmental Protection Agency 2007). Because of this decision, CO_2 must now be regulated under the Clean Air Act (*Clean Air Act* 1963). This premise has led to a particular political framing around climate change as a problem of managing several types of air pollution in the US, which emphasizes a definition of climate change as an emissions problem. Market-based approaches, specifically emissions trading, have become a favored policy tool for reducing air pollution. Since CO_2 is now considered an air pollutant, it is not surprising that similar approaches to air pollution management have been proposed for managing CO_2 as well, even though this only addresses half of the climate change problem. Understanding the history of US air pollution management, how CO_2 came to be recognized as an air pollutant, and how emissions trading has been involved in managing climate change today can help with understanding the process by which climate change could be reframed, and in ways that allow for additional management approaches. In particular, if we understand climate change as a two-part problem, then mechanisms for reducing CO_2 atmospheric concentrations would need to be adopted in addition to those that effectively reduce emissions.

Political Framing and Emissions Trading Policy

During the 1960's and early 1970's, market-based approaches like emissions trading were only an economic theory (Gorman and Solomon 2002). Several economists discussed the auctioning, trading, and selling of pollution rights both in air and water. They realized that allowing the market to set the social cost of pollution could be just as, if not more, effective as using the economic incentive of a direct tax on that pollution. If the market was used to cost effectively attain an environmental quality objective, it could be a promising idea (Gorman and Solomon 2002). The goal of market-based approaches is to "provide a given level of environmental protection at minimum cost for society as a whole" (Hahn and Stavins 1991). There was a time when market-based approaches were framed as a "license to pollute" or were deemed impractical (Hahn and Stavins 1991), and some still believe so today in the case of climate change (Lohmann 2006). Climate change is more likely to elicit this reaction because the only acceptable emissions are zero or even negative. Therefore, any allotment of emissions seems questionable. However, in the late 1980's before CO_2 emissions were regulated, emissions trading became much more popular as a cost effective means of reducing air pollution (Hahn and Stavins 1991). The ultimate goal of climate change policy and most environmental policy is to be "scientifically effective, economically rational, and politically feasible" (Stavins 1997). However, the hierarchy of these priorities can change depending on the policymaker or presidential administration implementing the policy.

The two main parts of a policymaker's role is to choose an overall goal in solving a problem and to choose the means to achieving that goal (Hahn and Stavins 1991). Framing is a communication and political technique used to simplify a complex issue in order to reach a decision (Nisbet 2010). It is an important first step for policymakers to proceed from an abstract problem to something that can be addressed within the political process. Frames give certain arguments more importance than others which helps to communicate why an issue is a problem and what policies can be used to solve the problem (Nisbet 2009). Framing has also been likened to agenda setting and is sometimes used interchangeably because of how it increases the importance of an issue while shaping how the public interprets the issue (Scheufele 1999).

At the interface of science and policy, Elisabeth Graffy defines framing as "a process of organizing available information, identifying knowledge gaps, and generally trying to structure understanding of an issue in ways that may involve cross-disciplinary and synthetic explanation" (Graffy 2008). Graffy's 2008 paper discusses an initiative within the US Geological Survey's National Water-Quality Assessment (NWQA) Program to increase its policy relevance. The communication and cultural differences between science and policy made it difficult for scientists to communicate their work in a way that would be useful for policymakers. Graffy developed a heuristic model (see Table 2) to show the relationship between the scientific and policymaking processes called the functions of scientific information (FOSI) model. The FOSI model is built on the basis that "policy makers view scientific information in terms of its functional value for achieving their goals of influencing or directly formulating and implementing legislation and rules that create or manage social change" (Graffy 2008). Therefore, in order to make their research results more policy relevant, the NWQA scientists needed to first increase their abilities in Stage 2 of the model: putting issues into perspective.

Table 2. Functions of Scientific Information Model (Graffy 2008)

	Stages of the Policy Process	**Corollary Functions of Science Information**	**Diagnostic Questions**
1	Issues emerge	Announce discoveries	What did you find?
2	Frame issues	Put issues into perspective	What does it mean?
3	Set priorities	Test decision options and scenarios	What matters? What can I do?
4	Legislate priorities/goals	Validate choices or trade-offs	What supports this position?
5	Implement goals	Enable implementation	Where? How?

Graffy's research reveals that while scientists are very experienced at creating information and announcing discoveries (Stage 1), if that information (even if it is inconclusive) is not effectively communicated or framed in a larger context that policymakers can understand (Stage 2), it most likely will not be useful to policymakers. It was clear to climate scientists as early as the 1820's that increased CO_2 emissions from burning fossil fuels were leading to increased global temperatures (Fourier 1824). It was also effectively communicated to policymakers by the 1990's that 2°C of global warming should be the maximum limit to prevent dangerous climate change effects and that drastically reducing emissions could achieve this goal (Rijsberman and Swart 1990; European Commission 1996).

It was also clear in the 1970's that CO_2 emissions remained in the atmosphere for hundreds of years and it is the accumulation of those emissions that ultimately leads to increased global temperatures (National Research Council 1977). However, this aspect of climate change has not been effectively communicated to policymakers. This is because in the 1970's there was still an ample amount of time to reduce emissions in order to stay below 2°C warming. By reducing emissions, there would be less accumulation of those emissions therefore preventing the increase of CO_2 concentrations in the atmosphere. At this point, scientists were proposing that the US begin lessening their reliance on fossil fuels and investing in renewable energy (National Research Council 1977); advice which supports the framing of climate change as an air pollution problem.

However, the US and the rest of the world remained reliant on fossil fuels and never reduced their emissions enough to prevent the increase of CO_2 concentrations in the atmosphere. These concentrations have now reached a saturation point that can no longer be prevented by reducing emissions (IPCC 2018). This saturation point has not been effectively communicated for policymakers to act upon most likely because it is much easier to grasp the concept of reducing emissions than removing past emissions from the atmosphere. Although the very beginnings of carbon dioxide removal research was mentioned in the 1970's as possible solution to reducing CO_2 concentrations (Nordhaus 1975; National Research Council 1977), there is no precedent for taking pollution out of the air. Therefore, policymakers are still framing climate change as an air pollution problem because it makes the most sense and has the attainable and actionable response of reducing emissions.

The following sections reveal how political framing has led to the increased use of market-based approaches for managing air pollution in the past, how this framing has encouraged their use for managing CO_2 emissions, and how it has influenced the overall framing of climate change as an air pollution problem. A summary of these political framings and their associated policy decisions can be found in Table 3.

History of Air Pollution Management in the United States

Clean Air Act of 1970

In 1943, a smog siege came to Los Angeles, California resulting in quickly increasing numbers of eye and throat irritation complaints (Brienes 1976). In 1948, severe smog fell over the city of Donora, Pennsylvania. Twenty people died and thousands of others were negatively affected (US EPA 2007). In 1952, London, England experienced a "Killer Fog" leaving over 3,000 people dead (US EPA 2007). These and several other events were the tipping points that led to the creation of the US Air Pollution Control Act of 1955 (US EPA 2015a). Since then, two more iterations occurred in 1963 and 1967 until the development of the Clean Air Act of 1970 under the creation of the Environmental Protection Agency (EPA). This act required the regulation of criteria air pollutants: particulate matter, ozone, sulfur dioxide, nitrogen dioxide, and carbon monoxide in 1971 (US EPA 1971).

When the Clean Air Act was created, the US began enforcing quantity based, command-and-control targets, resulting in increased costs of pollution control (Stavins 1997; US EPA 2015a). National Ambient Air Quality Standards (NAAQS) were created to determine how much of each criteria air pollutant was allowed in the air before harming the public health and environment. However, several areas were not able to attain the new air quality standards. These command-and-control standards began to limit economic growth by keeping new businesses from entering non-attainment areas. Due to the unintended consequence of NAAQS, an immediate solution was needed to manage non-attainment areas while still holding the areas in attainment accountable (Gorman and Solomon 2002; Tietenberg 2010).

In 1976, California created the Offset Interpretative Ruling allowing new stationary sources of emissions to exist in nonattainment areas as long as they maintained the lowest emission rate possible and offset their emissions elsewhere within their facility or by purchasing offsets from another facility (Gorman and Solomon 2002). Thus, emissions trading was born; the first time this economic theory was put into practice. California's program was adopted by the EPA within the Clean Air Act Amendments of 1977 (Gorman and Solomon 2002). Much trial and error occurred in developing the EPA's emissions trading policy until its finalization in 1986 (Hahn and Stavins 1991). This program was successful in finding a way for industries to expand within nonattainment areas without increasing emissions in those areas, balancing economic growth and air quality (Tietenberg 2010).

Phase out of leaded gasoline 1979-1987

The adverse effects of lead on public health caused its first regulation as an auto fuel additive under the CAA in 1973 (US EPA 2007; Hahn and Stavins 1991; Environmental Law Reporter 2011). At the same time, car manufacturers began implementing catalytic converters to comply with CAA emission standards. This created a need for unleaded gasoline in order to prevent damage to the catalytic converters (Nriagu 1990; Gorman and Solomon 2002). The EPA began phasing out lead in gasoline in the mid 1970's (US EPA 2007). While at this point lead was regulated as an auto fuel additive under the CAA, it was not regulated as an air pollutant. This changed after the 1976 court case of Natural Resource Defense Council vs. EPA Administrator Russell Train requiring lead to be regulated as an air pollutant due to its "adverse effect on health" and was added to the list of criteria air pollutants in 1978 (US EPA 2016a; Environmental Law Reporter 2011).

Restrictions on leaded gasoline increased in the 1980's (US EPA 2007), therefore increasing the cost of command-and-control regulations by forty percent between 1984 and 1991 (Hahn and Stavins 1991). In 1989, the Bush Administration discussed promoting the increase of market-based approaches in the Clean Air Act. Many policymakers began to consider that market-based approaches may be more cost effective. During the Bush administration, improving domestic productivity and reducing federal budget deficits were of great concern. Therefore, using the government's budget to further support existing environmental policies was unfavorable (Hahn and Stavins 1991). In addition, cost effectiveness was a very important value to the Republican party that the Bush Administration supported (Hahn and Stavins 1991). Therefore, the administration's framing of market-based solutions as cost effective means to reducing lead pollution initiated the use of emissions trading for leaded gasoline.

The EPA used their authority to require oil refiners to reduce their lead averages during gasoline production. A trading program for lead was now needed to help small oil refineries keep up with the change in the market. Small refineries purchased lead credits from large refineries so they could continue using lead in their gasoline and not have to purchase the expensive equipment needed to increase the octane of the gasoline without using lead. Lead trading allowed more flexibility in meeting emission standards while leaded gasoline production decreased. While technically the lead additive was traded rather than emissions, the lead ended up as an emission in the long run, therefore making a case for considering it a form of emission trading (Gorman and Solomon 2002). The

EPA continued to lower the cap on the lead average to keep up with the increase in the numbers of catalytic converters. However, the lead trading program was scheduled to end on December 31, 1987 for a complete phase out of leaded gasoline (Hahn and Stavins 1991; Tietenberg 2010). Lead emissions trading was successful in reducing leaded gasoline in preparation for its phase out.

Phase out of CFCs 1989-1995

A large cut in world production of Chlorofluorocarbons (CFCs) was needed after scientists discovered their effect on the stratospheric ozone layer. CFCs were mainly used as refrigerants, and also for propellants for aerosol spray cans. Other uses include cleaning agents for electronics and manufacturing semiconductor chips (Plummer and Busenberg 2000; Sunstein 2007). The ozone layer is the atmospheric barrier that protects the earth from harmful ultraviolet sunlight. The use of CFCs breaks down this barrier, resulting in exposure to ultraviolet radiation and a dramatic increase in skin cancer risk (Sunstein 2007).

Starting in 1985, scientific consensus concerning damage to the ozone layer increased. Research showed evidence of an ozone layer hole hovering over Antarctica that was the size of the US. The Montreal Protocol was signed in 1987 to set June 30, 1998 as the deadline to cut CFC production to 50% of 1986 levels (Sunstein 2007; Tietenberg 2010). Similar to the phase out of leaded gasoline, emissions trading through transferable permits was used as a catalyst for CFC reduction (Sunstein 2007; Tietenberg 2010). Industrialized countries were able to trade with developing countries that needed more time to reduce their CFC production. Due to the small number of CFC producers, there was not a lot of emissions trading activity. Most trading occurred between 1991 and

1995 between the US company Dupont and the Canadian company Dow Chemical (Gorman and Solomon 2002). The imagery of a hole in the ozone layer and the fear of skin cancer stirred the public to voluntarily participate in the phasedown as well by reducing their aerosol can purchases (Sunstein 2007).

The political framing of reducing CFCs as a health precaution was a major driver to use market-based approaches for CFC reduction. By 1990, nearly the entire world was convinced of the dangers of CFCs and the evidence that more was needed to be done to curb their damage, leading to an agreement to eliminate their production and use by 2000 (Gorman and Solomon 2002; Sunstein 2007; Tietenberg 2010). The firm phase out date from the Montreal Protocol added to its great success by influencing CFC producers to act earlier than necessary in reducing their production to prepare for their eventual ban. In 1989, a tax on sold and used CFCs was also implemented (Tietenberg 2010). These tactics drove major CFC production companies, like the US company DuPont, to create substitutes for CFCs. However, some believe DuPont already had a CFC substitute which encouraged the US to push for more stringent Protocol rules (Gorman and Solomon 2002; Sunstein 2007).

Sulfur Dioxide Cap-and-trade Program 1992-present

Acid rain was first discovered in the US in the 1960's through the study of Hubbard Brook in New Hampshire (Likens and Bormann 1974). In the 1980's scientists reached a consensus that the sulfur dioxide (SO_2) emitted from coal and oil fired power plants was able to decrease the pH of precipitation (Schmalensee and Stavins 2013; Gorman and Solomon 2002). This acid rain severely damaged several natural resources, particularly freshwater lakes and streams, coastal estuaries, and forests, resulting in loss of fish and aquatic life, algal blooms, loss of vegetation for aquatic habitats, and increased disease and mortality of trees (Chestnut and Mills 2005). In response to this concern, a cap-and-trade program was created within the Clean Air Act Amendments of 1990 to cut sulfur dioxide emissions in a cost-effective manner. The EPA introduced a cap on SO_2 emissions, 50% of 1980 levels, which slowly tightened thereafter. This cap-and-trade program gave power plants allowances for the amount of SO_2 they were allowed to emit. If they went over that amount, they were required to buy more allowances from another plant who emitted less than the allowances they received.

During the creation of this program, there was no credible information available to estimate what SO_2 reduction target would be most economically beneficial. This lack of information was true for most developing environmental policies (Schmalensee and Stavins 2013). Furthermore, in many cases politics came ahead of science and economics in making policy decisions. Policies were designed to succeed in the political atmosphere of the time. Cap-and-trade gained political support due to its ability to appease both environmental and economic constituencies (Schmalensee and Stavins 2013).

Therefore, the cap was chosen using the economic theory of the abatement cost curve, which was believed to determine the target at which emissions could be maintained at the lowest cost possible (Schmalensee and Stavins 2013). In effect, it is a trade-off between cost of abatement which rises as the cap is tightened and environmental or health damage which decreases as the cap is tightened. The SO_2 cap-and-trade program is still used today to control SO_2 emissions. Although there were reservations of how well the trading program would lower emissions, it has been very successful. Without the trading program, emissions from 1990 levels would have increased marginally through 2010. The program has led to greater human health benefits than expected (Chestnut and Mills 2005).

History of Carbon Dioxide Management in the United States

Massachusetts v. EPA

While environmental protection was heightened in the 1990 Clean Air Act amendments, the EPA did not yet recognize greenhouse gases as a threat to public health and welfare. In 1999, private environmental organizations petitioned the EPA to regulate CO_2 and other greenhouse gases from new motor vehicles under Section 202 of the Clean Air Act. Section 202 requires the EPA to regulate air pollutants from new motor vehicles that may threaten public health or welfare (Abate 2008).

The EPA did not accept the petition, arguing that they did not have the authority to manage climate change. They also argued that the link between increased greenhouse gases and global warming was uncertain (Abate 2008). However, the case, Massachusetts v. EPA, worked its way up to the Supreme Court. On April 2, 2007, the Court determined that greenhouse gases were considered “air pollutants” under the Clean Air Act and ruled that the EPA reconsider the petition by determining whether or not greenhouse gas emissions from new motor vehicles endanger the public health or welfare (Watts and Wildermuth 2008; US EPA 2016b).

December In 2007, towards the end of the George W. Bush administration, the EPA’s endangerment finding concluded that greenhouse gas emissions from new motor vehicles were a danger to the public welfare and therefore should be regulated under the Clean Air Act. They did not conclude that the emissions were a danger to public health due to scientific uncertainty. However, the endangerment finding was never made public due to the backlash the administration was receiving from the fossil fuel industry and political pressure from within the administration (Samuelsohn and Bravender 2009). Instead the administration released an Advanced Notice of Proposed Rulemaking stating they would defer action on the endangerment finding to the incoming President (Markey 2008). The decision was finally made public in October 2009, ten months into the Obama Administration (Samuelsohn and Bravender 2009).

On December 7, 2009, the EPA Administrator under President Obama, Lisa Jackson, signed a new endangerment finding concluding that greenhouse gases from new motor vehicles threaten both the public health and welfare, while the EPA was only required to find whether the emissions threaten one or the other to require regulation. Jeff Holmstead, the former EPA air chief under the Bush administration, believed that the Obama endangerment finding was too aggressive since the science was still uncertain as to whether climate change endangered public health. He believed that the Obama administration concluded both to express its great concern about climate change and support its environmental constituency (Samuelsohn and Bravender 2009). It could also be so that the administration had greater executive power to implement climate change policy since other climate policies were not successful in Congress (Bartosiewicz and Miley 2014).

The final rule went into effect on January 14, 2010, which led to implementing greenhouse gas emission standards for vehicles (US EPA 2016b). The 2014 Supreme Court case, Utility Air Regulatory Group v. EPA, further ruled that the EPA was also required to regulate greenhouse gas emissions from stationary sources as long as those sources were previously regulated for pollutants within the National Ambient Air Quality Standards (Buzbee et al. 2015).

The Clean Power Plan

Political framing was used throughout Barack Obama's presidential campaign to communicate to voters about the importance of creating climate change policy. Obama framed climate change as an opportunity for creating new green jobs and fueling the economy (Nisbet 2010; Bomberg and Super 2009). He supported biofuels research and increased targets for renewable energy (Bomberg and Super 2009). However, his framing focused much more on consuming and creating clean energy than conserving or reducing energy use. Going beyond addressing environmental concerns, this framing also reflected the American values of security, national interest, and energy independence. By addressing climate change within the context of these more urgent and politically appealing objectives, this framing gave Obama a better chance of passing climate change policy (Roman and Carson 2009). While the framing emphasized positive outcomes, it did not put much emphasis on the costs and sacrifices needed to reduce greenhouse gas emissions, most likely to appease voters (Bomberg and Super 2009) but may have instead emphasized renewable energy as a way to avoid greenhouse gas emissions.

Once Obama became President, the hope was that Congress would pass its own cap-and-trade legislation for CO_2 or more broadly for greenhouse gases. However, the bills that were proposed never passed the Senate. One interpretation for the lack of success in the legislative branch was because of a lack of grassroots and public support. In any case, the proposed bills did not reduce emissions to the standards that scientists deemed necessary (Bartosiewicz and Miley 2014). There was also a lack of public support on climate change issues due to a lack of understanding of global warming (Selin and VanDeveer 2007). Since legislation on climate change issues was not forthcoming, the Obama administration ended up exercising its own authority to regulate CO_2, which largely rested on the requirement that the EPA consider CO_2 emissions as air pollutants.

In 2009, EPA Administrator Lisa Jackson announced plans to use her new authority under the Clean Air Act to establish regulations for greenhouse gas emissions for the entire energy sector (Walsh 2009). The Clean Power Plan (CPP) was introduced in 2015 under the Obama Administration which exercised the EPA’s new authority to establish regulations for greenhouse gas emissions for the entire energy sector. The CPP encouraged the increased use of natural gas as a less carbon intensive alternative to coal and the increased use of renewable energy as a zero-emission strategy (US EPA 2015b). States were welcome to create their own plans for reducing emissions based on the goals set by the CPP, or they could follow the federal plan created by the EPA. The federal plan focused on market-based approaches, specifically a mass-based emissions trading program. Mass-based emissions trading was encouraged based on the more than 20 years of successful experience the EPA has had using this approach for several pollutants including sulfur dioxide, nitrous oxide, and mercury (US EPA 2015d). Obama’s framing of climate change as an economic opportunity could be another reason why the use of a cap-and-trade policy was recommended. The fossil fuel industry prefers emissions trading over alternative regulations like taxes and fees or command-and-control options (Walsh 2009; Hahn and Stavins 1991), giving them more control over how they reduce their emissions. Emissions trading is therefore seen as a pathway to reducing emissions without stifling economic growth.

Even though the EPA had the power to regulate emissions, the Clean Power Plan has always been seen as a temporary solution until Congress passes its own legislation. Many environmentalists believe the Clean Air Act was never meant to regulate climate change (Walsh 2009), as CO_2 poses a very different problem than most conventional air pollutants. On the other hand, the Clean Air Act also showed quite some flexibility when the lead additives in gasoline became subject to the Act and were treated as air pollutants.

In the end, the Clean Power Plan was never implemented due to its suspension in the US Supreme Court in 2016 and the US Court of Appeals DC Circuit in 2017 (US EPA 2019d). 150 groups filed against the plan including 27 states, 24 trade associations, 37 rural electric co-ops, and three labor unions, due to technical and legal concerns (US EPA 2019d). Coal and oil producing states such as West Virginia and Texas testified that the plan would make a significant negative impact on their economies (Hurley and Volcovici 2016). The Supreme Court ruled 5-4 to halt the plan while the DC Court of Appeals continued to review its legality. This was the "first time the Supreme Court stayed a rule that was still under review in a lower court" (US EPA 2019d), and the first time the court has ever blocked an EPA rule (Hurley and Volcovici 2016).

However, there were also many entities that supported the CPP through court briefs. These supporters included the EPA, several states and municipalities, power companies, tech companies, consumer brands, business associations, energy and health experts, faith communities, and 193 members of Congress (Environmental Defense Fund 2020). Even after the CPP was later repealed, states continued their commitments to clean energy. In particular, New Mexico, New York, Washington, and the District of Columbia are "requiring all electricity that utilities sell to consumers be generated from carbon-free energy sources, such as wind, solar and nuclear power, by 2050 or earlier" (Quinton 2019). Maine, Nevada, and Colorado are enacting similar laws, and Hawaii and California are continuing their commitments to 100% clean energy (Quinton 2019).

Affordable Clean Energy rule

During Donald Trump's presidential campaign, he framed climate change as a hoax and claimed that human activities had little if any connection to global warming (Goode 2016). He expressed strong support for coal miners and proposed to help them keep their jobs by investing in coal (Bump 2016). One of his goals was to undo many of Obama's policies including the CPP (Goode 2016). In 2019, President Trump repealed the CPP and replaced it with the Affordable Clean Energy rule (ACE). The ACE focuses specifically on reducing CO_2 emissions from coal-fired power plants by using technologies to increase their efficiency. Aligning with Trump's framing of climate change, the ACE does not mention any market-based approaches to reducing emissions. Instead, it uses a command-and-control approach by giving a list of technologies that coal-fired electricity generating plants can use to increase their efficiency (US EPA 2019a; 2019b). Although a command-and-control approach is used to require certain technologies, the requirements are as relaxed as possible to keep coal plants running with as little interruption as possible while also aligning with the Clean Air Act.

The Green New Deal

The Green New Deal (GND) is a climate resolution that has been introduced in the US House of Representatives, and it is framed to draw a direct comparison to the New Deal created under former President Franklin D. Roosevelt to help the US recover from the Great Depression (Ocasio-Cortez et al. 2019). The GND declares that it is the duty of the federal government to provide economic and environmental justice through the basic needs of clean air and water, a sustainable environment, an opportunity for economic growth. This resolution has framed climate change as a problem that has "exacerbated systemic racial, regional, social, environmental, and economic injustices" (Ocasio-Cortez et al. 2019). It makes a strong connection between the environment and the economy and how both can be improved by combating climate change. One of the main ways the GND plans to mitigate climate change is to achieve net-zero greenhouse gas emissions by removing them from transportation, infrastructure, energy sources, manufacturing, and agriculture (Ocasio-Cortez et al. 2019). In the GND, justice is equated with the elimination of greenhouse gas emissions.

Since the Green New Deal is a resolution, it is only a statement of aspiration and has not been passed into formal law like the CPP and ACE and therefore does not give specific policy measures for achieving its goals. However, Bernie Sanders, a 2020 presidential candidate and supporter of the Green New Deal, recommends charging the fossil fuel industry for their pollution through taxes and fees (Sanders 2020). This policy recommendation directly relates to the framing of justice by holding the fossil fuel industry accountable, even though the taxes and fees will most likely be passed through to the consumer. However, this still supports the framing of climate change as a pollution problem by putting pressure on the fossil fuel industry to reduce their emissions.

Table 3. Political Frames of Air Pollutants

Air Pollutant	**Problem**	**Policy Objectives**	**Policy Solution**
Air pollutants (particulate matter, ozone, sulfur dioxide, nitrogen dioxide, and carbon monoxide)	• Reduced air quality • Health concern	• Cost effectively improve air quality • Allow non-attainment areas to accept new businesses to maintain economic growth	• Market-based solutions (emissions trading)
Lead	• Reduced air quality • Health concern	• Maintain economic growth while improving air quality	• Emissions trading for leaded gasoline phase-out
CFCs	• Hole in ozone layer • Skin cancer health concern	• Maintain economic growth while reducing health concerns	• Montreal Protocol: emissions trading for CFC phase-out
SO_2	• Acid rain from fossil fuel burning	• Cost effectively reduce acid rain	• Emissions trading (cap-and-trade)
Greenhouse Gases (GHGs)	• Climate change • GHGs endanger public health and welfare	• Reduce GHGs	• Massachusetts v. EPA: Manage GHGs under CAA air pollutants • Reduce GHG emissions like other air pollutants
CO_2	• Climate change • Economic opportunity	• Increase natural gas • Increase renewable energy • Create new green jobs • Reduce GHGs • Maintain flexibility in approach	• Clean Power Plan: market-based solutions (emissions trading), states can determine how to meet performance targets
CO_2	• Climate change • Climate change is a hoax	• Maintain use of fossil fuels • Keep coal jobs	• Affordable Clean Energy rule: Command-and-control • Increase efficiency of coal plants
GHGs	• Climate change • Injustice	• Fix climate change while also increasing environmental and social justice	• Green New Deal: Net-zero by 2050

Environmental Effectiveness of Emissions Trading

Because of the prominent role emissions trading had in air pollution control in the US, and that the same concepts are also applied to managing CO_2, which is now also considered an air pollutant, it is useful to categorize various emission trading programs or strategies according to how they are implemented. All emission trading either explicitly or implicitly starts from a scheme to account for emissions and assign them to a facility. These facilities either own or can purchase an emissions budget and trade any excess budget in one facility against a shortfall in another. This implies some form of emission limit against which trading proceeds. The challenge for CO_2 emissions is that the limit is rapidly approaching zero, and very likely could go negative.

The emissions trading programs of today can be categorized into three types: reduction credit, averaging, and cap-and-trade. Reduction credit programs allow facilities to earn credits for reducing their emissions more than is required. Facilities with credits can then trade their credits with other facilities that are not able to reduce their emissions to the required amount. The credits that these other facilities purchase count toward their compliance. (Ellerman, Joskow, and Harrison Jr 2003). In this case, each facility has been assigned a limit and emissions trading may be needed to stay in compliance. Emission trading makes it possible for the facilities with the lowest cost of reductions to perform the task. Since emissions are locally assigned, it can be difficult for policymakers to manage the total emission allowance in such a scheme. It becomes easy to allow for total emissions in excess of what is desirable.

In averaging programs, higher emitting facilities and lower emitting facilities trade emissions to achieve a set average emissions level. Averaging programs and reduction credit programs are very similar except that averaging programs are automatically certified without the need of an administrative process while reduction credits are certified on a case by case basis (Ellerman, Joskow, and Harrison Jr 2003). In this implementation, policymakers can focus on the total allowed emissions but could tighten targets so much that the price of an emission skyrockets.

In cap-and-trade programs, a cap is put on the amount of emissions that facilities can create. This cap sets the amount of allowances that are distributed to all existing facilities. Allowances are distributed for free or through an auction. Each facility must have enough allowances to account for all of their emissions. Facilities that need more allowances can purchase them from other facilities with extra allowances (Ellerman, Joskow, and Harrison Jr 2003). By generating allowances the policymaker in effect defines an emission budget. By changing the number of allowances available, the policymaker can effectively control the price of an emission.

Now that CO_2 is defined as an air pollutant, emissions trading has become a recommended approach to manage CO_2 emissions due to the political and economic success of emissions trading in the past. There are several studies that explain this past success by measuring the effect of various climate change policy approaches to reduce emissions. In a study comparing thirteen global climate change policy approaches, it was found that market-based approaches should be the main focus of policy implementation, specifically taxes (Aldy, Barrett, and Stavins 2003). Another study evaluating eight policy approaches for carbon emission mitigation discussed that emissions trading that required participants to purchase auctioned permits could result in lower costs and higher environmental benefits than if permits were distributed for free (Parry and Williams

1999). In this study, the effectiveness of the carbon tax was equated to emissions trading with auctioned permits and was found the most cost effective and environmentally beneficial approach (Parry and Williams 1999).

However, in 1960, economist Ronald Coase reasoned that using a tax on pollution is not always the most effective solution. Allowing participants to consider alternatives and negotiate solutions themselves would result in a better outcome. Therefore, such an outcome would more likely occur using emissions trading (Gorman and Solomon 2002). Other economists still believed that a pollution tax could create a result just as economically ideal as emissions trading. However, it is important to think about the purpose of the market-based approach. A tax allows the market to determine the limit on pollution rather than choosing a predetermined limit to maintain environmental quality. Cost effectively maintaining a fixed limit on pollution would be best achieved using emissions trading (Gorman and Solomon 2002). Furthermore, a recent study in the United Kingdom concludes that even if a very high tax is put on CO_2 emissions, it will only help to lower emissions in the short term, but will not be able to maintain long-term emission reductions to keep global warming under 2°C. Instead, the tax must be paired with incentives to develop and deploy carbon dioxide removal strategies to reduce global warming (Daggash and Mac Dowell 2019).

The history of emissions trading in the US was successful in reducing criteria air pollutants and SO_2 as well as eliminating leaded gasoline and CFCs which contribute to poor air quality, harm to natural ecosystems, and serious health concerns. Emissions trading is generally used as a cost effective way to facilitate the transition time to phase-out or phase-down a substance along with integrating an alternative substance (Toman and Palmer 1997). A “phase-out” is the transition period toward banning a harmful substance like CFCs and leaded gasoline. A “phase-down” is the transition period toward reducing a harmful substance to a safer level like SO_2.

However, not all phase-outs needed emissions trading to be successful. For example, the use of transferable permits was considered in the asbestos ban rule (US EPA 1989), but it was rejected because of increased administrative costs and creating significant administrative problems, removing it as a least burdensome option. The EPA concluded that creating a permit system for all products containing asbestos would be very difficult to enforce. Furthermore, some asbestos products present a higher risk than others do which would be difficult to control under an overarching permit system. Instead the EPA implemented a rule within the Toxic Substances Control Act that “prohibited the manufacture, importation, processing, and distribution in commerce of most asbestos-containing products in three stages over 7 years” (US EPA 1994).

Another example is the case of the popular pesticide Dichloro-diphenyl-trichloroethane (DDT). Once DDT was discovered to have negative environmental side effects, the EPA set to ban it effective in June 1972. The date was then delayed until December 31, 1972 to allow more time for transition to alternative pesticides (US EPA 1972). However, DDT usage was already declining before the ban date due to insect resistance and development of better substitutes (US EPA 1975). This may be a reason why emissions trading was not necessary to ban the pesticide.

In the case of CO_2, facilities that can emit at least 75,000 tons per year of CO_{2e} under the Clean Air Act requirements (US EPA 2011) are easily identifiable, manageable, and should not cause administrative strain that the asbestos ban perceived.

While there are renewable energy alternatives to fossil fueled electricity like there were substitutes for DDT, there are still several economic, political, technical, and social barriers to deploying renewables at the rate needed to replace fossil fuels. Perhaps the lack of alternatives for CFCs and leaded gasoline was the reason for using emissions trading. Therefore, as renewable energy becomes cheaper and more readily available, emissions trading may become less necessary. Emissions trading may be best used as a transition tool for phase-out until alternatives are available. However, until alternatives are available, the cap or emissions target should continually decrease to enforce emissions reductions.

In terms of phasing down a pollutant, emissions trading may reduce harmful emissions, but it still encourages their creation. For example, emissions trading is still used to manage SO_2 emissions. The program continues to succeed at keeping SO_2 emissions at a safe level, but a further reduction in emissions is needed to protect the vulnerability of natural resources (Chestnut and Mills 2005).

A 2003 study found that the reduction of acidification in the Adirondack lakes of New York was directly driven by SO_2 emission reduction from the 1990 Clean Air Act Amendments (Driscoll et al. 2003). The decreases in SO_2 emissions have allowed an increase in the acid neutralizing capacity (ANC) of the lakes. ANC values of 50 μequiv L^{-1} are best for protecting aquatic life, however the study also revealed that in 2000, "34 of the 48 lakes had mean ANC values of <50 μequiv L^{-1}, including 10 lakes with ANC values <0 μequiv L^{-1}" (Driscoll et al. 2003). The study calculated that lakes with 0-50 μequiv L^{-1} would take approximately 3-50 years to reach 50 μequiv L^{-1}, while chronically acidic lakes with <0 μequiv L^{-1} would take approximately 25-100 years to recover

(Driscoll et al. 2003). While the study does show that SO_2 emissions trading was helpful in reducing acidification, it will still take several decades to reverse environmental harm, especially if SO_2 is continually emitted at the same rate. Therefore, it could be beneficial to reevaluate the limit of SO_2 emissions prescribed under the SO_2 emissions trading program to decide if the current limit on SO_2 emissions is enough, if the limit should be increased, or if it is necessary to ban SO_2 emissions.

While acknowledging the success of emissions trading for SO_2's smaller, short term reductions, Lohmann explains that reducing CO_2 emissions needs a much larger solution. This requires a change in technology and society that allows fossil fuels to be left underground. Instead, emissions trading allows the fossil fuel industry to continue polluting. Lohmann raises an important question: "Why [would industries] bother making expensive long-term structural changes if [they] can meet [their] targets by buying pollution rights from [other] operations that can cut their carbon cheaply?" (Lohmann 2006). Lohmann argues that industries will not bother to reduce their emissions targets if pollution rights are still available and affordable. Therefore, emissions trading may not be a strong enough solution on its own.

However, Lohmann's argument exchanges one goal for another. Net zero emissions of CO_2, or even net negative emissions of CO_2 do not require that all fossil fuels are left underground. Indeed, the need to create net negative emissions requires the introduction of negative emission technology that can equally well be used to balance residual emissions from fossil fuel use. While it is a fair question to ask whether the continued use of fossil fuels should be allowed in the future, the reason for insisting on keeping fossil carbon in the ground cannot be solely justified with concerns over climate change. If CO_2 emissions can be avoided and CO_2 levels were reduced from current levels by negative emissions technology, the climate problem would be eliminated whether or not fossil fuels are phased out. One can make the argument, that climate change is not the only issue associated with fossil fuel use that in balance it would be better to avoid their use. However, this reasoning needs to be justified by other arguments than climate change. It is a separate and very different question whether the economic constraints of introducing negative emissions are such that they in effect lead to the phasing out of fossil fuels.

One of the reasons the Montreal Protocol was so successful was because of its firm phase-out date (Tietenberg 2010). This deadline is what made manufacturers serious about finding new alternatives to CFCs. Without a deadline, there would be no incentive for manufacturers to put in the work in finding alternatives. In the same vein, emissions trading for CO_2 could discourage innovation and instead encourage using the cheapest technologies that allow facilities to stay just within the CO_2 limit. To encourage innovation, it would be important that the CO_2 limit be reduced over time. It would likely be helpful and spur innovation, if a timeline would be set that would demand that CO_2 emissions are balanced by net negative emissions after a certain period of phase in.

Myles Allen at the University of Oxford has made the suggestion that for every ton of carbon coming out of the ground a rising fraction of a ton of carbon will have to sequestered (M. R. Allen, Frame, and Mason 2009). Lackner et al proposed a similar idea where allowances for CO_2 emissions would be gradually phased out, but could be replaced with certificates of sequestration (K. S. Lackner, Wilson, and Ziock 2001). Allen proposes a rapid increase in the fraction of fossil fuels that needs to be balanced by sequestration, until after some time negative emission technologies prevent the further accumulation of CO_2 in the atmosphere. In effect, such an approach drives the cap in a cap-and-trade system to zero (M. R. Allen, Frame, and Mason 2009). What is different to other cap-and-trade systems, is that negative emission technologies can create a tradeable commodity even after the cap has become zero. Therein lies the difference between the trading of offsets or allowances and the trading of carbon removal. Just introducing a static cap on CO_2 emissions would only focus on short-term success and fail to take into consideration the long-term solutions needed for climate change (Driesen 2002; Lohmann 2009). In the case of SO_2 control, command-and-control regulation was needed to encourage innovation for reducing SO_2 emissions (Taylor, Rubin, and Hounshell 2005). As Lohmann suggests, the same will be for CO_2.

Learning from the Montreal Protocol and the phase-out of asbestos in stages over the course of seven years, CO_2 will need a firm phase-down schedule for long-term success. For example, if a fossil fuel plant knows that 80% of their CO_2 emissions must be reduced in 30 years, and within that 30 years emissions must be reduced by 27% every 10 years, emissions trading can be used to help with the transition. However, the plant may also be more likely to invest in innovative long-term strategies to reduce their emissions on time. This uses the best practices of emissions trading and firm deadlines from both phase-down and phase-out examples.

However, due to the US' dependency on fossil fuels and without an easy transition to alternative energy sources to prevent CO_2 emissions, it is very unlikely that the preferred way of stopping climate change is the banning of fossil fuels. Instead a cap-and-trade system that allows for the gradual introduction of negative emission technologies would make it possible to combine phasing out of fossil fuels where it makes economic sense with balancing out those emissions which are hard to eliminate directly. The CPP was President Obama's course of action to make this transition. The plan was estimated to reduce emissions by 415 million tons of CO_2 by 2030 (US EPA 2015b). However, the plan was never implemented due to its suspension in the US Supreme Court in 2016 and the US Court of Appeals DC Circuit in 2017 (US EPA 2019d).

The ACE replaced the CPP in June 2019 and is estimated to reduce 11 million tons of CO_2 by 2030 (US EPA 2019c), 404 million tons less than the CPP. However, in August 2019, 29 states and cities sued the Trump Administration for "easing restrictions on coal-burning power plants" and weakening the regulations established by the CPP (Friedman 2019b). The case argues that the ACE "ignores the EPA's responsibility under the law to set limits on greenhouse gases" (Friedman 2019b).

The Green New Deal aims for the US and the world to become net zero by 2050. However, the resolution was blocked from further consideration by the US senate in March 2019 (Friedman 2019a). Nevertheless, several presidential candidates in 2020 support the resolution and incorporated it into their platforms (Sarlin 2019). It has also been supported by several grassroots environmental organizations led by Sunrise Movement (Moe, Sotomayor, and Shabad 2018).

Since the GND is a resolution and not a specific policy, it is hard to estimate what it could achieve and how difficult it would be to reach its suggested targets. However, if warming is to be limited to 1.5°C it will become necessary to approach net zero emissions around the year 2050. At the current rate of emissions, the world will reach

450 ppm CO_2 in the atmosphere in about 15 years. At 450 ppm the world likely exceeded its 1.5°C warming limit. If the world could achieve a linear rate of reduction in annual emissions it would have to reach zero in less than 30 years from now if the CO_2 concentration in the atmosphere should reach its maximum at or below 450 ppm. If this is the target for the world as whole, global equity would demand an even more stringent target for a country that has been responsible for a disproportionately large fraction of all cumulative emissions since the beginning of the industrial revolution.

Conclusion

The political framing of climate change shapes the types of policies that are likely to be implemented. Framing climate change as an air pollution problem has led to solutions like the CPP, ACE, and the GND which focus on reducing emissions. Neither of them has incorporated steps to reduce CO_2 concentrations. A policy focused on the polluter can be efficient in reducing emissions from different sources, but it is ill suited for lowering the concentration of CO_2 in the atmosphere. Even if introduced to balance out current emissions, it encounters resistance as it appears to go against the grain of a narrative that blames the problem on the polluter.

Since the 1970's, market-based approaches have been used significantly to cost effectively improve air quality in the US. Leaning on these successes, emissions trading has been recommended as a solution for managing CO_2 emissions and it is suggested that it is more effective than other policy approaches in its ability to establish a limit on emissions. Once the Supreme Court ruled that CO_2 must be regulated by the EPA, emissions trading was recommended under the Clean Power Plan, the country's first plan created to abide by the court's ruling. This recommendation has also been influenced by the political framing of climate change as an opportunity for economic growth, emphasizing the increase of renewable energy and development of green jobs while concurrently using emissions trading to reduce emissions and appease the fossil fuel industry. In contrast, the Trump Administration frames climate change as a hoax and that the coal industry should be protected which is shown in the Affordable Clean Energy rule. In ACE, emissions trading is not used and instead the policy returns to a weak command-and-control approach, reducing significantly less CO_2 than estimated for the CPP. However, even the ACE approach is informed by framing climate change as an air pollution problem.

By framing climate change as a justice issue, the Green New Deal resolution gives solving climate change even more urgency than the CPP did. The Green New Deal sets the most ambitious of climate change mitigation goals by working to achieve net zero global emissions by 2050 but it is only a resolution and does not give explicit policy recommendations on how to achieve this goal. However, it is the only plan that sets targets that could help stay within the 1.5°C limit set by the Paris Agreement. Overall, it is clear that emissions trading is an effective means of reducing emissions, but it is also important to recognize the importance of political framing which carries the responsibility to guide climate change policy in the right direction.

By framing climate change as an air pollution problem solved by reducing emissions, climate change will never be resolved. Emissions trading is a helpful tool to reduce emissions but is only one piece of the larger climate change solution. The next chapter explains the scientific reasoning behind why reducing CO_2 emissions must be paired with reducing atmospheric concentrations in order to effectively combat climate change, how political framing can help to emphasize the importance of this pairing, and what technologies are needed to reduce emissions and concentrations.

CHAPTER 3

REFRAMING CLIMATE CHANGE TO IMPROVE THE MANAGEMENT OF BOTH CARBON DIOXIDE EMISSIONS AND CONCENTRATIONS

Introduction

Chapter 2 explains the importance of political framing in how climate change is perceived and what policies should be implemented to mitigate it. Recent political framings have led to CO_2 emissions reduction through dependence on natural gas and emissions trading within the Obama administration and increased efficiency within the Trump administration. The Green New Deal expresses goals to achieve net zero emissions by 2050. However, these framings have led to incomplete solutions. Reducing CO_2 emissions is only half of the solution to combating climate change. The other half of the solution is reducing CO_2 concentrations. The current framing of climate change and an air pollution problem does not emphasize the need for concentration reduction. Although the Green New Deal does discuss using afforestation and soil carbon storage to remove greenhouse gas emissions from the atmosphere, it is only as a means to emissions reduction to achieve net zero emissions, not concentration reduction. The climate change problem should be reframed to incorporate CO_2 concentration reduction as an essential part of climate change mitigation.

Reframing the Climate Change Problem

Again, there are two goals for CO_2 management with regard to climate change mitigation. First, is to reduce CO_2 emissions as much as possible. Second, is to reduce CO_2 concentrations from past emissions in the atmosphere. As explained in Chapter 2 using the FOSI model, one of the reasons why current climate change framing does not incorporate concentration reduction may be because the science of climate change is not fully translated for policy purposes (Graffy 2008). It is well understood that CO_2 emissions contribute to climate change, but the lifetime and concentration of those emissions is not often explained. Defining CO_2 as an air pollutant under the Clean Air Act gives the impression that CO_2 is only characterized as an emissions issue and the EPA should only manage the emissions aspect of climate change. What this policy approach fails to address is the difference between emissions and concentration. While CO_2 emissions created the problem of climate change, it is the high concentration, the buildup of those emissions over hundreds of years, that perpetuates the problem of climate change. The EPA's regulatory scope must be widened in order to fully combat that reality.

The most important difference between historical air pollution problems and emissions contributing to climate change are the lifetimes of the emitted gases in the atmosphere. As seen in Table 4, CO_2 has a much longer lifetime than emissions from other air pollutants discussed in Chapter 2.

Table 4. Atmospheric Lifetimes of Well-Known Air Pollutants

Emission	**Atmospheric Lifetime**	**Source**
Criteria Air Pollutants	Few days-few weeks	(Stocker 2014)
SO_2	4-12 hours	(Fioletov et al. 2015)
CFC	45-1020 years	(Stocker 2014)
CO_2	100-1000+ years	(US EPA 2015c)

To more effectively tackle climate change as a whole, environmental policies must address the high concentration of CO_2 that is sitting in the atmosphere and remains there year after year. It is this concentration and not the rate of emissions that causes the negative effects associated with greenhouse gases such as global warming, sea level rise, and increased natural disasters (USGCRP 2017; Rogelj et al. 2018). Even if the use of fossil fuels completely stopped and CO_2 emissions were phased out today, the negative effects from the concentration of past CO_2 emissions that are currently in the atmosphere will continue for at least 1,000 years (Gillett et al. 2011; MacDougall, Eby, and Weaver 2013; H. D. Matthews and Zickfeld 2012; Solomon et al. 2009; Eby et al. 2009). Therefore, climate change must be reframed to promote policies that not only reduce CO_2 emissions, but also CO_2 concentrations which requires removing CO_2 from the atmosphere.

Policy and Technology Strategies for Reframing the Climate Change Problem

Positive Emissions

Several technical and economic policy strategies address both emissions and concentration reduction. However, it is important to understand what level of reduction each strategy can achieve. As listed in Table 5 and seen in Figure 2, continuing to burn fossil fuels as well as steel production increases CO_2 emissions, creating positive emissions. There are several strategies for emissions reduction including energy efficiency, lowering energy consumption, emissions trading, and carbon capture, utilization, and storage. When paired with fossil fueled power plants, carbon capture and storage (CCS) prevents a majority of CO_2 generated during combustion from entering the atmosphere and stores this CO_2 permanently. However, while all of these strategies reduce emissions, emissions are still created which results in positive emissions. None of these strategies can lower the CO_2 concentration in the atmosphere.

Emissions Trading for Emissions Reduction

Emissions trading is not a helpful solution for reducing emissions if it perpetuates the creation of CO_2 emissions. CO_2 emissions need to be stopped unless the limit on those emissions is satisfactory for mitigating climate change. Unfortunately, as long as there are emissions, the accumulation of excess CO_2 in the atmosphere will continue. All emissions trading programs have some kind of "cap" or limit to the amount of emissions that can be created. However, as the atmosphere reaches a CO_2 concentration level that threatens the ability for humans to live on the earth, this cap should equal zero. Due to the high concentration of CO_2 in the atmosphere, the only satisfactory limit is zero emissions. In other words, there should be no more CO_2 emissions allowed in the atmosphere, which means emissions trading of excess allowances that would be allowed under the cap ceases to exist. The only possible trade is in balancing CO_2 emissions with equal and opposite carbon dioxide removal. This, however, is very different from a conventional cap-and-trade approach. If CO_2 emissions were phased out and conventional emissions trading were no longer possible or necessary, then there would be only one goal to focus on: tackling the excessively high concentration of CO_2 in the atmosphere.

Zero Emissions and Negative Emissions

Renewable energy technologies and nuclear energy are zero emissions technologies, meaning no CO_2 emissions are created when using those technologies. In today's world this is a slight exaggeration, because both energy systems involve supply chains which in turn rely on energy and concrete that were produced at least in part from CO_2 emitting processes. However, as the energy system is gradually transformed, these technologies will gradually approach truly zero emissions.

Negative emissions technologies (NETs) such as direct air capture and storage (DACS) and bioenergy with carbon capture and storage (BECCS) are the technologies under the umbrella of carbon dioxide removal (CDR) that can achieve negative emissions, net zero emissions, and net negative emissions by managing CO_2 concentrations in the atmosphere. Negative emissions is the anthropogenic removal of CO_2 emissions from the atmosphere (J. B. R. Matthews et al. 2018). NETs directly remove CO_2 from the atmosphere in any location and store it permanently. NETs can achieve net zero emissions, also known as carbon neutrality, by balancing CO_2 emissions so that the same amount of CO_2 emitted into the atmosphere is also removed (J. B. R. Matthews et al. 2018). In achieving net negative emissions, NETs go further and remove more CO_2 from the atmosphere than is emitted (J. B. R. Matthews et al. 2018). Carbon capture and utilization can achieve net zero and net negative emissions if the CO_2 is captured using NETs (Minx et al. 2018) and the fate of the CO_2 removed from the environment is such that it remains permanently sequestered in storage sites or in long-lived products. The utilization of the carbon, such as in a product, must keep the carbon stored for many years to be considered a negative emission. Longevity of storage is important, but if CO_2 is again released it can be removed and stored again. In order to avoid future climate change from the accidental or planned release of stored carbon, storage times have to be many thousands of years (K. S. Lackner et al. 2012).

Table 5. Technology and Policy Solutions for CO_2 Emission and Concentration Reduction

Positive Emissions		Zero Emissions	Negative Emissions	
Burning fossil fuels	Emissions Reduction	Renewable energy	Net Zero Emissions (Emissions Reduction)	Net Negative Emissions (Concentration Reduction)
Steel production	Energy efficiency	Nuclear energy	Direct Air Capture, Utilization, and Storage	
	Lowering energy consumption		Bioenergy with Carbon Capture, Utlization, and Storage	
	Emissions trading			
	Carbon Capture, Utlization, and Storage			

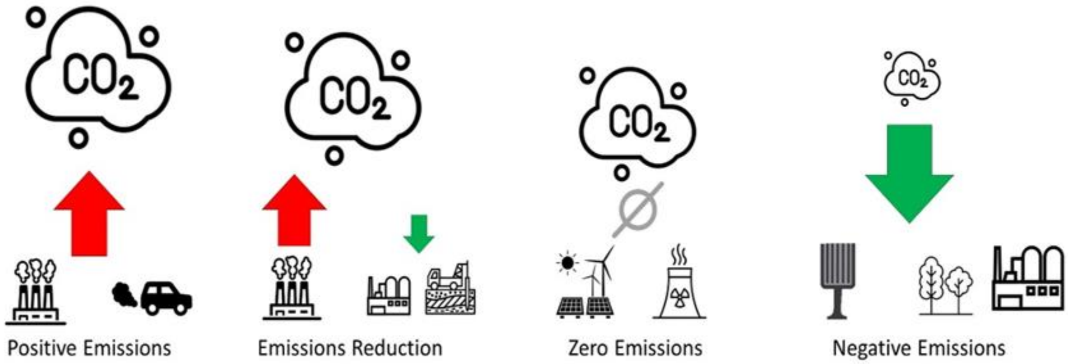

Figure 2. Carbon Accounting of Various CO_2 Management Technologies

While all the technologies and strategies discussed can help to reduce the creation of CO_2 emissions and approach carbon neutrality, only NETs are capable of being net negative by removing more CO_2 emissions from the atmosphere than are created. More importantly, achieving net negative emission is the only way to reduce CO_2 concentrations. It is also important to clarify the difference between CDR and CCS (Figure 3). While the CDR and CCS titles are sometimes used interchangeably and both include CO_2 capture and storage processes, they are not the same. CCS is a technology that is added to existing fossil fueled power plants to reduce emissions by capturing the CO_2 from the power plant itself either before or after combustion occurs (Leung, Caramanna, and Maroto-Valer 2014). CDR encompasses NETs which removes (i.e. captures) past CO_2 emissions from the atmosphere (J. B. R. Matthews et al. 2018), therefore reducing CO_2 atmospheric concentrations. To ensure that CCS is not assumed to achieve net negative emissions, it is best to keep CCS and CDR categories separate.

Carbon Dioxide Removal	
Removal (Negative Emission Technologies)	**Storage**
Direct air capture	Geological reservoirs, Products
Bioenergy with carbon capture and storage	
Afforestation/reforestation	Terrestrial reservoirs
Soil carbon sequestration	
Biochar	
Enhanced weathering	Minerals
Ocean fertilization	Ocean reservoirs

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Carbon Capture and Storage	
Capture	**Storage**
Pre-combustion	Geological reservoirs, Products
Post-combustion	

Figure 3. Differentiating Carbon Dioxide Removal and Carbon Capture and Storage

Along with BECCS and DACS, there are several other NET options including afforestation and reforestation, enhanced weathering, ocean fertilization, biochar, and soil carbon sequestration. Afforestation and reforestation are a slow-going solution as trees cannot fulfill their full CO_2 capture potential until they are fully grown. This solution is also limited by land use constraints and unreliable carbon storage due to natural and human disturbances such as forest fires and land use change. Enhanced weathering is currently only in the theoretical stages and has many uncertainties. Ocean fertilization is not now seen as a viable solution as it has a low reliability for sequestration. Furthermore, the sequestration potentials for biochar and soil carbon sequestration are either unreliable or unknown. Therefore, this chapter focuses on BECCS and DACS due to their technical reliability and use of reliable storage techniques for permanent storage. BECCS and DACS are also the most used NETs in current models and strategies for staying below 1.5°C of warming (IPCC 2018; National Academies of Sciences, Engineering, and Medicine 2019).

Negative Emission Technology's Potential to Reduce CO_2 Emissions and Concentrations

According to the US Energy Information Administration's International Energy Outlook 2019, the world will emit 43.085 Gt of energy related CO_2 in the year 2050 (US Energy Information Administration 2019). Many studies also report that CCS has the potential to capture ~90% of CO_2 emissions from electricity generating fossil fueled plants (Rao and Rubin 2006; Leung, Caramanna, and Maroto-Valer 2014). Furthermore, Fuss et al. reports that the 2050 global potential for NETs, (BECCS and DACS), will be 5 Gt CO_2 each (Fuss et al. 2018).

While there are many different estimates of NET potential, this chapter uses the extensive literature review and synthesis of NETs from Fuss et al. to determine the potential of BECCS and DACS technologies in 2050. While the actual technical potential of BECCS and DACS is quite large and almost unlimited for DACS, the potentials given by Fuss et al. also account for social, economic, and environmental constraints synthesized from a large pool of literature (Fuss et al. 2018; Minx et al. 2018). Specifically, BECCS can be limited by land constraints and increased emissions from land use change, and DACS by storage constraints, unintended environmental consequences, and land constraints (Fuss et al. 2018).

Adding the maximum potentials of both BECCS and DACS together is already outside the bounds of Fuss et al. as these maximum potentials assume "global land governance, integrating multiple land use concerns for the global common good" (Fuss et al. 2018). Furthermore, BECCS and DACS could be in competition for land and storage, so adding the potentials pushes against these constraints. Overall, the potentials given in

Fuss et al. “should be interpreted as deployment ranges that are feasible in the context of generally favorable conditions, i.e. long-term policy support, with key decisions made in the technology cycle and deployment phase to generate demand pull, and few social, economic or environmental shocks in the relevant agricultural and land use sectors” (Fuss et al. 2018). Taking all of this into consideration, the following analysis shows how the assumed maximum potential of BECCS and DACS in 2050 matches up with forecasted energy related CO_2 emissions.

In Figure 4, the blue bar shows the 43.085 Gt of energy related CO_2 emissions expected for 2050. This bar also considers the amount of CO_2 avoided from using renewable energy technologies. The orange bar shows the 12.05 Gt maximum potential of CO_2 emissions avoided using CCS, which can remove 90% of CO_2 emissions created from the expected electricity generation in 2050 that still relies on fossil fuels. The green bar shows the 10 Gt maximum potential of CO_2 emissions avoided using NETs (adding together the potentials of BECCS and DACS). The grey bar shows the 21.03 Gt of CO_2 emissions that will still enter the atmosphere after using CCS and NETs at their maximum potentials.

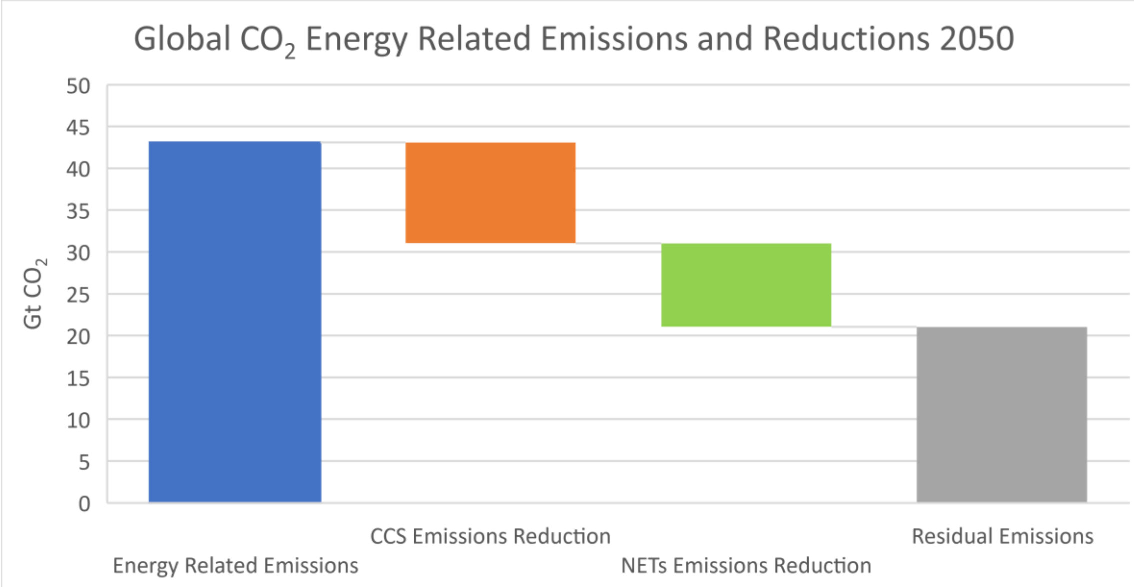

Figure 4. Global CO_2 Energy Related Emissions and Potential Reductions in 2050

According to the potentials given by Fuss et al, NETs are only able to be used for emissions reduction rather than concentration reduction due to the excess amount of CO_2 emissions that will be generated in 2050. This figure shows that even if CCS and NETs are used to their fullest potential, they will not be enough to achieve net negative results in 2050. There will still be an excess of ~21 Gt CO_2 going into the atmosphere.

This analysis also shows the difficulty in achieving carbon neutrality. Even after allowing for 10 Gt of CO_2 per year of negative emissions, the scenarios analyzed by Fuss et al. failed to balance the world's carbon budget. It is therefore important to ask whether the limits to negative emissions are hard limits imposed by physical laws or whether they are due to assumptions on how fast technologies tend to grow and what costs they might have in the future. As was noted by the National Academies study on NETs, there are no inherent physical limits to removing CO_2 from the atmosphere at rates necessary to balance the world's carbon budget (National Academies of Sciences, Engineering, and Medicine 2019). The same argument has been made by Lackner et al as early as 1995 (K. S. Lackner et al. 1995).

As has been pointed out by Mark Jacobson and Cristina Archer, the total number of available wind sites on the planet could support a wind energy infrastructure that could easily produce as much power as the world consumes today (Jacobson and Archer 2012; Archer and Jacobson 2005). The CO_2 content of the air processed by these windmills would exceed the world's CO_2 emissions by two orders of magnitude (K. S. Lackner et al. 2012; K. Lackner, Ziock, and Grimes 1999). All these arguments suggest that the capture of CO_2 from air does not introduce serious limits on the scales that can be reached. Similarly, the National Energy Technology Laboratory's Carbon Dioxide Storage Atlas indicates that there is more than enough storage space to dispose of all the CO_2 that is collected (National Energy Technology Laboratory 2015).

Therefore, one is left with the question of how fast could such an industry grow to reach world scale. This question is hard to answer, but there are a number of examples where infrastructures were developed over the course of a couple of decades. France converted from fossil energy electricity generation to nuclear energy in less than two decades. Therefore, while it would be challenging to reach 20 or 40 Gt of CO_2 removal per year by 2050, given the right economic incentives it certainly could not be ruled out, and in any case, total withdrawal rates could easily double once a decade for several decades to come after the 2050 deadline has been passed. This emphasizes once more the need for negative emissions. Therefore, rather than suggesting that NETs cannot reach the necessary scale, a better reading of the analysis by Fuss et al. is that there is a strong need to accelerate the development and deployment of NETs.

Figure 4 is therefore a representation of the need for more investment in CO_2 mitigation and net negative emissions solutions in order to fulfill the concentration reductions necessary to combat climate change. However, as mentioned before, even if all CO_2 emissions were avoided using renewable energy and CCS, the need for net negative solutions will still be necessary to remove the abundance of old CO_2 emissions sitting in the atmosphere (Solomon et al. 2009). The 2018 global average of atmospheric CO_2 was 407.4ppm (~3181.8 Gt) (National Oceanic and Atmospheric Administration 2019). The Organization for Economic Cooperation and Development predicts that atmospheric CO_2 levels may reach ~530ppm (~4139.3 Gt) by 2050 (OECD 2012). The 2050 potential capacity of NETs is not enough to handle the new emissions created in 2050 let alone the trillions of tons of CO_2 already in the atmosphere.

While the use of CCS, renewable energy, energy efficiency, and other mitigation strategies are important, there are still many processes that these solutions cannot decarbonize including “aviation, long-distance transport, and shipping; production of carbon-intensive structural materials such as steel and cement; and provision of a reliable electricity supply that meets varying demand” (Davis et al. 2018). The current mitigation strategies are not enough to manage the emissions from these ongoing processes. This intensifies the need for NETs as an important contribution to both emissions and concentration reduction. There is a need to not only heavily reduce new emissions, but to also remove old emissions from the atmosphere and emissions from processes that cannot be decarbonized on their own.

Skeptics of Negative Emission Technologies

Research conducted by Mark Jacobson disagrees with the use of NETs, specifically DAC (Jacobson 2019). His research shows that certain energy intensive implementations will increase CO_2 emissions and other pollutants when powered by fossil fuels and if powered by renewables, pollution and social costs will still increase. Therefore, according to his analysis only replacing fossil fuels with renewable energy (without using DAC) can reduce CO_2 emissions, pollution and social costs.

However, there are a number of issues one needs to address. First, it is true that the DAC device considered by Mark Jacobson requires so much fossil energy that it produces roughly half as much CO_2 as it captures from the air. However, it is worth noting that this CO_2 is also captured and removed. Moreover the same criticism that a windmill consumes more energy than it produces was leveled against early models as well and if policymakers had listened to these arguments from fossil fuel competitors, neither wind or solar energy would have made it out of the prototype phase. Moreover, it is important to note that there is a difference between CO_2 avoidance and CO_2 removal. Replacing fossil fuels with renewable energy is helpful and necessary for getting to net-zero emissions but still does nothing to reduce CO_2 concentrations currently in the atmosphere.

Jacobson does discuss that DAC can be used to remove CO_2 from the atmosphere when fossil fuels are no longer in use. As long as renewables are used to power DAC, there will be no increased air pollution. In addition, Jacobson notes that the social cost of DAC may be more expensive than that of planting trees, another strategy for reducing CO_2 concentrations. However, the point that there is not enough land available to raise a sufficient number of trees has been made rather widely (IPCC 2019; K. S. Lackner 2009; Friedlingstein et al. 2019). In Jacobson's study, social costs include energy, health, and climate costs (Jacobson 2019). A substantial fraction of the costs he points to are not related to CO_2 emissions. Unfortunately, such cost analyses depend critically on measuring differences between the cost of different options, and here Jacobson seems to assume that the cost of intermittent wind energy is small and that environmental, social and health costs can safely be ignored. In any case, the study of social cost is outside of the scope of this research, however, storing CO_2 underground after using DAC has a greater permanency than CO_2 storage within trees (Fuss et al. 2018). This could in turn result in a lower social cost for DAC.

Anderson and Peters believe that relying on NETs takes emphasis away from other mitigation strategies necessary for combating climate change. NETs present an "unjust and high-stakes gamble" as to whether they can actually deliver the amount of CO_2 removal that integrated assessment models are predicting (Anderson and Peters 2016). However, most scientists do not promote full reliance on NETs, nor do they see NETs as a quick fix to solving climate change (Buck 2012; National Academies of Sciences, Engineering, and Medicine 2019). Instead it is a complement to other mitigation strategies in order to reduce both CO_2 emissions and concentrations. Rejecting NETs could be leaving out an important part of the solution to mitigating climate change (K. S. Lackner 2016). Moreover, while Anderson and Peters promote mitigation and lifestyle changes, it is far from clear that they offer feasible solutions. Lifestyle change on the energy front has been promoted at least since the first oil crisis with very little results to show for.

It is certainly true, that NETs have not yet proven themselves. So far nobody has asked for them, and therefore it is not surprising that the technology has not yet been developed. The question is not whether NETs are ready to be deployed, but whether policies that advance these technologies are worth implementing.

Incorporating NETs as a Policy Strategy in the Reframing of Climate Change

Current US policy has not been paying enough attention to NETs as part of the solution to climate change (Peters and Geden 2017; D. W. Keith, Ha-Duong, and Stolaroff 2006; Kriegler et al. 2013). Scott argues that strategies from the past show how governments have intervened in order to move technologies forward such as nuclear power, flue gas desulphurization, and renewable energy technologies. Tactics such as command-and-control approaches, funding, taxes, and planning for guaranteed decarbonization are necessary. The current stagnation of NET development shows that current government action is insufficient (Scott 2013).

What makes creating policy for NETs difficult is that there is no precedent for governing the removal of air pollutants. Current policies are focused on regulating the activities of facilities that deposit pollutants into the atmosphere (Hester 2018). Permits under the Clean Air Act and various other environmental policies are only issued for facilities that generate pollutants, not for removing them. This lack of precedent can be a barrier, but there are existing regulatory systems that can inform CO_2 removal.

<u>National Ambient Air Quality Standards</u>

After the US Supreme Court ruled that CO_2 should be regulated as an air pollutant under the Clean Air Act, stationary sources like power plants are now required to have greenhouse gas permits if they have the potential to emit at least 75,000 tons per year

(TPY) of CO_{2e} (US EPA 2011). This unit of measurement does not take into consideration how these tons of CO_2 will contribute to the concentration of CO_2 in the atmosphere, nor does it take into consideration the lifetime of this CO_2 in the air. National Ambient Air Quality Standards (NAAQS) are required for criteria air pollutants which do consider concentration over a certain amount of time, albeit only 1 hour up to 1 year (US EPA 2014b), but there are no NAAQS established for CO_2 in order to limit CO_2 concentrations (US EPA 2011).

However, the idea of creating NAAQS for greenhouse gas emissions is not new. The Center for Biological Diversity and 350.org petitioned the EPA to create NAAQS for greenhouse gas emissions, specifically setting CO_2 concentrations at 350 ppm (Center for Biological Diversity and 350.org 2009). Other scholars have also thought out how to implement NAAQS for CO_2 (G. F. Allen and Lewis 2009; Raiders 2010; Crystal et al. 2018).

Leaders within the Center for Biological Diversity Climate Law Institute discussed that the implementation of NAAQS for CO_2 is well within the means of the Clean Air Act (Crystal et al. 2018). A set limit on CO_2 concentrations can be determined based on the reduction needed to stay within 2°C of global warming since it has already been agreed upon by most of the world under the United Nations Paris Agreement. The EPA will then have to determine what CO_2 concentration standard should be used to achieve this goal (Crystal et al. 2018; Raiders 2010).

Many disagree with creating NAAQS for CO_2 because the entire US will be in non-attainment and will incur many costs to get to 350 ppm (Center for Biological Diversity and 350.org 2009; Crystal et al. 2018; G. F. Allen and Lewis 2009; Raiders

2010). Also, due to the long lifetime of CO_2 in the atmosphere, it will take decades to reduce concentrations to 350 ppm. However, within the NAAQS guidelines, the EPA is not allowed to consider costs when creating NAAQS (G. F. Allen and Lewis 2009). Furthermore, NAAQS allow an averaging time for states to achieve attainment. The Center for Biological Diversity Climate Law Institute explains that if the standard "allowed for seventy years of non-attainment over an averaging time of one-hundred years, then so long as attainment has been achieved in year seventy and maintained for the following thirty years, states will have been in attainment over the entire period" (Crystal et al. 2018).

While it would be difficult to implement and maintain NAAQS for CO_2, these standards take advantage of what the Clean Air Act has to offer and holds the EPA accountable for managing what the Supreme Court has defined as an air pollutant. Furthermore, if NAAQS were implemented, DAC could be added to the list of technologies that the EPA requires to control and reduce air pollutants under the Clean Air Act (US EPA 2016c). Without NAAQS, there are no standards that legally enforce a safe concentration level for CO_2 in the atmosphere. NAAQS could be a necessary part of the broader solution to reducing and monitoring CO_2 concentrations for climate change mitigation.

Other Regulatory Measures

Although there are many cost and regulation difficulties in integrating NETs into climate policy, they should not be a deterrence to move forward. NETs add flexibility and opportunities to reduce costs in reaching mitigation goals (Lomax et al. 2015). Even more so, delaying this action could make the integration more difficult in the future (Lomax et al. 2015; Hester 2018).

One of the most important steps in creating policy for NETs is to incorporate carbon accounting and liability for carbon leakage. This includes using measuring and monitoring techniques to account for CO_2 removal and storage, minimizing any unintended damage, and having liability mechanisms for storage failure (Meadowcroft 2013). One legal mechanism to achieve this step is using fault (Hester 2018). When facilities emit CO_2, they are at fault for contaminating the air. Therefore, they should be responsible for "cleaning up" what they emitted.

In order to finance CO_2, clean up through the federal government, removal of harmful pollutants from the air could be classified as a public good. A common way of maximizing a public good is to give economic value to the resource being produced, in this case the capture of CO_2 from the atmosphere, which reduces atmospheric concentrations. This can be done through carbon credits, emission trading, or ownership of the resource (Hester 2018).

In order to increase the deployment of NETs, the service of removing CO_2 should require payment. This incentive can also help to lower the price of carbon, which is needed to achieve the United Nation's Paris Agreement. However, one of the moral hazards associated with NETs is that it will prolong the use of fossil fuels. Therefore, fossil fuel use must also be discouraged to make NETs effective (Daggash and Mac Dowell 2019).

Conclusion

The only way to reduce CO_2 concentrations in the atmosphere is to achieve net negative results by implementing NETs which can remove more CO_2 from the atmosphere than is added. Although emissions reduction strategies are important, they cannot be the only solution used for climate change mitigation. They must be coupled with solutions that also reduce CO_2 concentrations. The characteristics of CO_2 emissions are much different than those of other air pollutants. The long lifetime of CO_2 emissions in the atmosphere increases the urgency for becoming net negative rather than only reducing CO_2 emissions.

CO_2 emission reduction strategies have helped to prevent higher CO_2 concentrations in the future, but they do not do anything to reduce current concentrations. A reframing of the climate change problem is needed to effectively manage CO_2 by putting a greater focus on CO_2 concentrations instead of only focusing on CO_2 emissions. Otherwise, policies to increase the use of NETs will never be put in place. Current regulations only focus on CO_2 emissions and are not equipped to reduce CO_2 concentrations.

There are various types of carbon management solutions that produce positive emissions, zero emissions, and negative emissions. The definitions of these solutions, how CO_2 is accounted for in each one, and what technologies can achieve them is important to consider when creating climate change policy. While this information may not be new on its own, it is crucial for understanding how to adequately combat climate change. There ineffective communication of differences between emissions and concentrations has shaped the policies put forth to combat climate change as ones that only focus on reducing emission. Therefore, a reframing of the climate change problem can help to show the importance of reducing concentrations as well as emissions. Furthermore, reframing climate change can assist policymakers to widen the scope of their environmental solutions to more effectively address climate change including increased research, development, and deployment of NETs for climate change mitigation.

Reframing the climate change problem for effective CO_2 management relies heavily on NETs to reduce CO_2 concentrations. However, NETs have uncertainties and negative consequences, even though they are heavily depended on to keep global warming to 1.5°C (IPCC 2018). Particularly, BECCS uses the natural CO_2 uptake of biomass to lower CO_2 concentrations. This requires a significant amount of land use for accommodating the amount of biomass needed. Extensive land use can affect food security, increased global food prices, burden water resources, and negatively impact biodiversity. Furthermore, the land use change and fertilizer needed to grow biomass produces CO_2 emissions and compromises the effectiveness of BECCS (Fuss et al. 2018). Therefore, the remainder of this research will focus on DAC. This research will also focus on geological storage due to its permanence in keeping captured CO_2 from returning to the atmosphere as compared to other storage techniques (Fuss et al. 2018).

CHAPTER 4

EVALUATING THE USE OF RESPONSIBLE INNOVATION FOR THE ETHICAL DEPLOYMENT OF DIRECT AIR CAPTURE

Introduction

Direct Air Capture (DAC) is necessary for reducing CO_2 concentrations, an essential piece to solving the second half of the climate change problem; the first half being reducing emissions. DAC can remove CO_2 that has been sitting in the atmosphere for hundreds of years so that it can be stored safely and permanently. However, before implementing new technologies into society, it is important to understand how they will affect the environment and its stakeholders.

Technological fixes have been known to create more problems instead of solving the problem it was created to solve (Sarewitz and Nelson 2008). However, there are certain instances where a technology can be instrumental in solving significant problems. Sarewitz and Nelson have developed three rules to determine whether a problem can be solved by technology:

1. "The technology must largely embody the cause–effect relationship connecting problem to solution" (Sarewitz and Nelson 2008).
2. "The effects of the technological fix must be assessable using relatively unambiguous or uncontroversial criteria" (Sarewitz and Nelson 2008).
3. "Research and development is most likely to contribute decisively to solving a social problem when it focuses on improving a standardized technical core that already exists" (Sarewitz and Nelson 2008).

Sarewitz and Nelson agree that DAC meets all of these criteria for solving climate change.

1. "Air capture embodies the essential cause–effect relations — the basic go — of the climate-change problem, by acting directly to reduce CO_2 concentrations, independent of the complexities of the global energy system" (Sarewitz and Nelson 2008).
2. "There is a criterion of effectiveness that can be directly and unambiguously assessed: the amount of CO_2 removed" (Sarewitz and Nelson 2008).
3. "Although air-capture technologies have been remarkably neglected in both R&D and policy discussions, they nevertheless seem technically feasible" (Sarewitz and Nelson 2008).

However, Sarewitz and Nelson do note that there are several technical, political, economic, and moral obstacles that must also be addressed when implementing direct air capture as well as other CDR and CCS technologies. These technologies are still emerging in their research and development with many unknown outcomes. Responsible Innovation (RI) is one ethics strategy to anticipate research outcomes through shared responsibility of stakeholders (Schomberg 2013). This research discovers whether RI is a valuable framework for the ethical deployment of DAC.

Background on Responsible Innovation

During the process of innovation, it is difficult to know what consequences will arise once that innovation is deployed to the public. Sometimes those consequences end up being much more damaging than would have been expected. Some researchers may try to excuse themselves from adverse consequences because they believe they could have no idea of future impacts. This moral debate uncovers the need for techniques that allow researchers to reflect on the intentions of their research and anticipate its outcomes (Owen et al. 2013).

Responsible Innovation (RI) is defined as: “A transparent, interactive process by which societal actors and innovators become mutually responsive to each other with a view to the (ethical) acceptability, sustainability and societal desirability of the innovation process and its marketable products in order to allow a proper embedding of scientific and technological advances in our society” (Schomberg 2013).

Jack Stilgoe offers a broader definition explaining that “Responsible Innovation means taking care of the future through collective stewardship of science and innovation in the present” (Stilgoe, Owen, and Macnaghten 2013).

There are four dimensions of Responsible Innovation:

Anticipation: Anticipation asks researchers to discover “what is known, what is likely, what is plausible and what is possible” in regard to their innovation. It “involves systematic thinking aimed at increasing resilience, while revealing new opportunities for innovation and the shaping of agendas for socially-robust risk research” (Stilgoe, Owen, and Macnaghten 2013). It encourages researchers to analyze the intended and unintended consequences that may develop economically, socially, and environmentally (Owen et al. 2013).

Reflexivity: Reflexive researchers are aware of the purposes and motivations of their research “being aware of the limits of knowledge and being mindful that a particular framing of an issue may not be universally held.” Reflexivity asks researchers to take moral responsibility for their innovations and seek out any areas of ignorance or assumptions they have made (Stilgoe, Owen, and Macnaghten 2013; Owen et al. 2013).

Inclusion/Deliberation: Inclusion involves public engagement. It allows the public and stakeholders to question the innovation and allows them to collaborate with the research during the innovation process (Stilgoe, Owen, and Macnaghten 2013; Owen et al. 2013).

Responsiveness: Responsiveness means to transparently react to and answer the questions that arise from the first three dimensions. This involves participatory governance, anticipatory governance, and adaptive learning (Stilgoe, Owen, and Macnaghten 2013; Owen et al. 2013).

Overall, RI creates a process where science and innovation is produced for and with society (Owen et al. 2013). RI may be a helpful tool for the development and use of DAC to understand its purpose and unintended consequences concerning climate change.

Responsible Innovation of Stratospheric Particle Injection

In order to evaluate the usefulness of RI for DAC, it is helpful to look at its use in the development of another emerging technology created to combat climate change: stratospheric particle injection. Stratospheric particle injection and DAC are both categorized under the umbrella of geoengineering. There are two subcategories of geoengineering: solar radiation management (SRM) and carbon dioxide removal (CDR). Stratospheric particle injection is a type of SRM while DAC is a type of CDR (Caldeira, Bala, and Cao 2013).

Stratospheric particle injection (also known as stratospheric aerosol injection) is the process of injecting sulfur particles into the stratosphere to produce a cooling effect by reflecting sunlight away from the earth, therefore reducing global warming (Caldeira, Bala, and Cao 2013). In 2011, Research Councils UK began a research project called Stratospheric Particle Injection for Climate Engineering (SPICE) to further discover the effectiveness and impact of stratospheric aerosols for SRM and proposing a field test of the technology using water (Stilgoe, Owen, and Macnaghten 2013). Following a RI approach, Research Councils UK decided to withhold funding for the project until further information was gathered using a stage-gate process. This process was used to understand the risks, regulations, purpose, future impacts, and public views of the technology before moving forward to a new stage of the project (Stilgoe, Owen, and Macnaghten 2013).

To satisfy the inclusion dimension of RI, members of the public in the United Kingdom (UK) were asked to participate in a public engagement study concerning the SPICE project. Participants said that SRM seemed “unnatural”, especially compared with CDR, and felt that international regulations should be created in case other countries were affected by the technology apart from the country that deployed it (Pidgeon et al. 2013). While many participants were willing to let the SPICE field test proceed using water, they also expressed concerns for future use of stratospheric aerosols, specifically for the safety of people on and near the test site and what would be done if something went wrong. This led to participants wondering whether it was even necessary to go through with the project when CDR and other emission mitigation strategies are also available. Participants also discussed their concerns about commercialization of SRM and the need for oversight of the global and environmental consequences of the technology (Pidgeon et al. 2013).

During the stage-gate process, the SPICE team continued to prepare for the field test. In response, project leaders received a letter signed by more than 50 non-governmental organizations demanding they cancel the project. The organizations felt that the field test was symbolically sending a message internationally that focusing attention on reducing greenhouse gas emissions was no longer necessary. Furthermore, a prior stratospheric particle delivery patent application had been submitted by researchers involved in the SPICE project. These incidents led to the cancelation of the project due to conflict of interest and lack of geoengineering research governance (Stilgoe, Owen, and Macnaghten 2013; Cressey 2012).

The stage-gate process used all four dimensions of responsible innovation. Anticipation, reflexivity, and inclusion were used throughout the process and responsiveness is the stage-gate process itself (Stilgoe, Owen, and Macnaghten 2013). This RI framework helped the research team to anticipate various impacts of the technology that they had not previously explored and reflect on their assumptions. The framework also developed a more reflexive and deliberative research culture within the SPICE team. This contributed to their decision to cancel the field test and has set a precedent for future geoengineering research (Stilgoe, Owen, and Macnaghten 2013).

Responsible Innovation of Direct Air Capture and Geological Storage

No published research was found concerning any DAC projects similar to SPICE or any DAC projects incorporating RI. However, there is published research concerning the risks, ethics, public perception, and governance of DAC research and deployment. This section categorizes these finding within the four dimensions of RI.

Anticipation

Many are wary of DAC because it is included as a form of geoengineering (also known as climate engineering) by removing CO_2 from the atmosphere, therefore a way of technologically manipulating the climate (Lomax et al. 2015; Minx et al. 2018; Adelman 2017). Geological storage, the process of storing the captured CO_2 underground, is also a controversial topic because of the effects it may have on underground water sources, the potential for earthquakes, and whether or not there is enough room underground to store all of the captured CO_2 (Fuss et al. 2018).

However, several publications assess these risks (McLaren 2012; Caldeira, Bala, and Cao 2013; Yousefi-Sahzabi et al. 2014; Franklin M. Orr 2009; Cooper 2009; Rayner et al. 2013). Many advancements have been made in proving how to directly remove CO_2 from the atmosphere (Yousefi-Sahzabi et al. 2014). Due to past experience in enhanced oil recovery, it has been proven that CO_2 can be stored underground permanently and monitored using current enhanced oil recovery techniques (Franklin M. Orr 2009; Cooper 2009). In regards to technical lock-in, DAC can be started or stopped at any time without causing harm to the environment or society (Rayner et al. 2013).

Reflexivity

Much of the ethical discussion surrounding DAC has been that it is a “moral hazard” against mitigating climate change. It suggests that using DAC may discourage other emissions reduction strategies because the technology can reduce emissions on its own, also giving an excuse for continued use of fossil fuels (Minx et al. 2018). However, most scientists agree that DAC and other geoengineering technologies are not a ‘silver bullet’ answer to the climate change problem, nor should they be an excuse to forego other emission reduction strategies (Buck 2012; National Academies of Sciences, Engineering, and Medicine 2019).

Inclusion

International research including the US has been done on the public perception of geoengineering, including DAC. Results show that public understanding and familiarity of geoengineering is low. While support for research and development of geoengineering technologies are positive, support for use of the technologies are low. However, there is greater preference for use of CDR over SRM. (Cummings, Lin, and Trump 2017; US Government Accountability Office 2011)

After giving a brief overview of SRM and CDR technologies to research participants in the UK, participants were concerned about the safety of the technologies and whether or not the changes to the environment could be reversed if something went wrong. They also wanted the technologies to be paired with emissions mitigation and not in place of them. Overall, participants saw CDR (which includes DAC) as a more "natural" solution to climate change and therefore gained more support than SRM technologies (Corner, Pidgeon, and Parkhill 2012; Parkhill et al. 2013).

Responsiveness

In response to the safety risks of geological storage, the US Environmental Protection Agency (EPA) established the Class VI well in 2010 under the Safe Drinking Water Act. Class VI wells are injection wells specifically for the geologic sequestration of CO_2 streams. A CO_2 stream is CO_2 captured from a source of emissions such as a power plant or industrial source through the process of carbon capture and storage (US EPA 2010). The EPA deemed CO_2 streams as solid waste when injected underground because it is a discarded and abandoned material (US EPA 2014a). Due to regulatory uncertainty of the hazardous waste potential of CO_2 streams, the EPA established a new rule in 2014 to conditionally exclude CO_2 streams from hazardous waste regulation as long as they are injected into Class VI wells for geologic sequestration (US EPA 2014a). While this rule does not discuss CO_2 captured using DAC, it would be reasonable to suggest that the rule would be applicable to CO_2 captured from the air.

Other than Class VI wells, the US does not have a federal governance strategy for geoengineering research or deployment. However, geoengineering research is being funded by several US agencies including the EPA and the Department of Energy (Bracmort, Lattanzio, and Barbour 2010; US Government Accountability Office 2010). Furthermore, the US created the 45Q tax credit in 2008 for carbon oxide sequestration from carbon capture, utilization, and storage projects. The tax credit was revised in 2018 to include DAC, allowing $35/ton of CO_2 stored through enhanced oil recovery and $50/ton of CO_2 stored permanently in geological formations (Larson 2018).

Therefore, there are federal rules in place to incentivize DAC, but no strategies to further monitor its safety and ethical use. The US Government Accountability Office and Congressional Research Service have researched and provided recommendations on geoengineering governance, but their work has not been implemented into any formal policy (Bracmort, Lattanzio, and Barbour 2010; US Government Accountability Office 2010; 2011). Therefore, the global science community has begun creating their own ideas for a governance strategy.

The Oxford Principles were created as a proposed way to govern geoengineering and have been endorsed by the UK Government (Rayner et al. 2013). Compared to the three other sets of principles that have been created, the Oxford Principles are argued to be the most comprehensive and influential (Heyward, Rayner, and Savulescu 2017). The principles were also generally endorsed by the international scientific community represented at the Asilomar Conference on Climate Intervention Technologies (Rayner et al. 2013). The five principles include (Rayner et al. 2013):

1. Geoengineering to be regulated as a public good.
2. Public participation in geoengineering decision-making.
3. Disclosure of geoengineering research and open publication of results.
4. Independent assessment of impacts.
5. Governance before deployment.

The Principles are criticized as vague because of the broad field of geoengineering that they encompass (“A Charter for Geoengineering” 2012). However, the authors purposely created abstract principles so that they can be tailored toward whichever technology is under consideration because a “one size fits all” approach would not be sufficient (Rayner et al. 2013).

More specific governance ideas have been created to progress geoengineering research by defining the difference between small and large projects and accepting government authority to avoid scientific self-governance (Parson and Keith 2013). However, these ideas still encompass all geoengineering, not any specific technologies. Furthermore, as long as the government does not make a decision on geoengineering governance, scientific self-governance will continue.

The need for governance becomes even more important as DAC becomes commercialized. To date, there are five companies globally that are commercializing their DAC technologies (National Academies of Sciences, Engineering, and Medicine 2019). As DAC enters the market, the narrative around the technology could change to protect capitalism (Buck 2012). In order to avoid increased regulation on fossil energy, the fossil fuel industry could push the idea that DAC is the only answer to defeating climate change, promoting "irresponsible entrepreneurial behavior" (Bracmort, Lattanzio, and Barbour 2013). This may already be happening as several fossil fuel companies have begun investing in DAC to remain profitable by becoming carbon neutral (Krauss 2019).

The DAC companies themselves could also be to blame. While some companies are committed to storing CO_2 underground permanently to be carbon negative, others are using the CO_2 to create fuels, building materials, and to sell to oil companies for enhanced oil recovery (Krauss 2019). Some of these uses can be considered carbon negative, but most are carbon neutral. Therefore, responsiveness is essential for maintaining the responsible innovation and deployment of DAC.

The Obstacles of Responsible Innovation

With the various steps required within RI and the difficulty to find consensus between scientists and the public (especially on climate change issues), one might say that RI impedes necessary research and technologies. How does RI make sure that the right technologies are pushed through and the wrong technologies are held back or discontinued?

When comparing SPICE to DAC, there are many reasons why one could argue that RI was used correctly to hold back SPICE from future deployment. From a technical standpoint, as discussed by Sarewitz and Nelson (Sarewitz and Nelson 2008), DAC provides a technical fix to climate change that is directly associated to the root of the problem by removing CO_2 from the atmosphere. On the other hand, SPICE uses particles to reflect sunlight away from the earth to reduce global warming but does not address the abundance of CO_2 in the atmosphere which is the actual cause of global warming. While both technologies do reduce global warming in the end, DAC is a much more sustainable approach to combating climate change.

Furthermore, the SPICE project was deemed dangerous to society. Stakeholders were concerned with the safety of the technology as well as the conflict of interest behind commercialization and its global consequences. While there are still societal concerns against DAC, nearly all of the safety concerns have already been met through previous research. In addition, the moral hazard and commercialization concerns could very well be satisfied through adequate US governance.

However, is it the job of RI to withhold technologies that could be necessary in a climate change crisis? If the US and the world does not achieve net zero emissions by 2050 and they wait too long to implement negative emission technologies, stratospheric particle injection could be the only chance to protect civilization. Stratospheric particle injection is cheaper than DAC and could be implemented much faster (D. Keith 2013). There is also much more research on specific governance strategies for solar radiation management than there is for carbon dioxide removal (Horton et al. 2018; Reynolds 2019; Barrett 2014; Jinnah, Nicholson, and Flegal 2018). In some respects, the US is better prepared to deploy stratospheric particle injection today than it is to deploy DAC. Therefore, while it is important for RI to monitor technologies and keep dangerous technologies from entering society, it should also allow research projects like SPICE to continue laboratory research and be prepared for potential deployment when absolutely necessary (Long, Loy, and Morgan 2015).

In the case of DAC, research and development should also be continued in hopes of deploying a more sustainable approach to climate change before a severe climate emergency arises. However, until proper governance for DAC is put in place, RI should be used to keep DAC from being deployed, therefore showing the urgency for governance and the political reframing needed to support such governance.

Even more so, RI should be a pathway to adequate governance of DAC, not an excuse to stall its deployment. RI should not be a means of holding technologies hostage, but instead a process of understanding what can be done to improve and monitor the technologies as well as deciding whether a technology should not be used. The process of RI has not kept DAC from deployment. Instead, the US' lack of governance has kept the RI process from completion. This should not be an excuse for DAC to never be deployed, but instead a push toward the necessary governance for responsible deployment.

Conclusion

The process of using RI within the SPICE project and the research published on the anticipated risks and public perception of DAC shows that RI is a valuable framework for ethically deploying DAC. However, if RI is used to stifle important research that could be useful in mitigating an emerging climate crisis, changes should be made to allow this research along with careful deliberation as to if and when the technology should be deployed. RI could be expanded to help align research priorities to the societal needs at hand and maintain preparedness for when crisis occurs. Otherwise, helpful adaptation efforts like the SPICE project could be missing from the toolbox of climate change solutions.

While RI can be used to maintain SPICE research for possible needs in the future, the US has not paid enough attention to the RI inspired research surrounding DAC. Research on DAC shows the technology is viable, safe, and preferred over SRM by the public. Nevertheless, public support for using DAC is low and there is a chance that the technology could be used more for profit than its ability to mitigate climate change. With respect to RI, DAC fulfills the anticipation, reflection, and inclusion dimensions, but responsiveness is missing.

It is no longer the science of DAC that prohibits its ethical deployment (National Academies of Sciences, Engineering, and Medicine 2019), but it is the lack of governance to oversee its ethical use. Without a nationally or globally recognized governance strategy for DAC, it will become increasingly difficult to make sure the technology is used for its intended purpose to mitigate climate change. If capitalism and planet protection do not mix (Buck 2012), governance strategies that support the reframing of climate change to include reducing CO_2 concentrations must be created to keep the fossil fuel industry and other affiliated parties from taking advantage of DAC for personal gain.

CHAPTER 5

CONCLUSIONS

By exploring climate change through political, technological, and ethical lenses, it is revealed that reduction of CO_2 emission and concentrations are not equally valued in climate change solutions. Political framing is an important strategy for shaping the way climate change is managed. The current framing of climate change as an air pollution problem has led to the increased use of emissions trading, but ignores CO_2 concentrations in the atmosphere. As long as CO_2 concentrations are ignored, climate change will never be resolved.

Although the science is clear that CO_2 concentrations must be reduced to stay within 1.5-2°C warming, the political framing of climate change has limited policy and technology solutions to those that only reduce CO_2 emissions. The scientific reasoning behind the need to reduce CO_2 concentrations has not been effectively communicated for policymakers to use for actionable climate change solutions. A new framing of the climate change problem is needed to bridge this gap between science and policy by encouraging the use of negative emission technologies which are the only technologies that can reduce CO_2 concentrations.

Direct air capture is an ideal negative emission technology to combat climate change by directly removing CO_2 from the atmosphere without dependence on biomass. Responsible Innovation is an effective framework for ethically deploying direct air capture technologies. It is a valuable framework for keeping dangerous technologies from deployment in society as it has done with stratospheric particle injection. More Responsible Innovation research is needed for direct air capture, especially for increased governance to ensure ethical deployment for the public good. However, Responsible Innovation can be improved by allowing continued research of emerging technologies, like stratospheric particle injection, that could be necessary in a time of a climate change emergency. Overall, this dissertation provides insight for reframing the climate change problem politically, technologically, and ethically in order to reduce CO_2 concentrations, increase investment in direct air capture, and increase deployment of direct air capture in an ethical manner.

A new political framing of the climate change problem is necessary to incorporate the need of CO_2 concentration reduction in addition to other CO_2 emission mitigation strategies. The air pollution framing leads only to strategies for reducing emissions or investing in renewable energy so that emissions are not created in the first place. However, what can be done after the pollution has already occurred, when the CO_2 is already in the atmosphere? The only example we have for this issue is waste management.

In general, waste management is the process of cleaning up and disposing of waste. Just as garbage is collected weekly from neighborhoods and Superfund sites are cleaned from previous hazardous waste, the US has governance structures that are responsible for managing waste. In the same vein, the US needs governance structures to manage the CO_2 "waste" that has been emitted into the atmosphere. NETs can provide the waste management service needed to clean up the atmosphere by removing CO_2 from the atmosphere thereby reducing CO_2 concentrations.

Political framing can assist in mobilizing this governance structure by framing climate change as a waste management issue (K. S. Lackner and Jospe 2017). This framing provides an easy way to understand how CO_2 is affecting the environment and how NETs can provide a technical solution. Ethically, this governance structure should be monitored by a governing body such as a Federal Carbon Board (K. S. Lackner, Wilson, and Ziock 2001), making sure that NETs are used as a public service, specifically to combat climate change.

Implementing a waste management governance structure in accordance with CO_2 emissions mitigation will require an eventual divestment in the fossil fuel industry. However, the great investment that the US has made in fossil fuels will make this a very difficult transition. The US has a long history of subsidizing fossil fuels dating back to 1789 (Pfund and Healey 2011). Subsidies are used to encourage the consumption and production of fossil fuels in the US. They also support the fossil fuel industry to maintain its infrastructure and sustain fossil fuel extraction (Erickson et al. 2017).

This investment in fossil fuels makes it easier to understand why countries would rather invest in anything else to reduce CO_2 emissions rather than divest in fossil fuels. For example, at their 2020 annual meeting in January, the World Economic Forum announced an initiative to plant one trillion trees to mitigate climate change. President Trump surprisingly supports the idea even though he has previously stated that climate change is a hoax. The reason that it was so easy to mobilize governments around the initiative is most likely because "it was practically sacrifice-free, no war on coal, no transition from fossil fuels, no energy conservation or investment in renewable sources of power…" (Friedman 2020). Creating a new framing around climate change that bridges the gap between science and policy and encourages the reduction of CO_2 concentrations could help to redirect the excitement around planting trees to the urgency for investing in

NETs. Furthermore, using a waste management structure gives a clear depiction of the climate change problem, allows trees to be a part of the solution, and also uses other NETs in the solution to provide more permanent capture and storage methods.

It is also important to remember that the US is very much capable of strategically utilizing resources in times of energy crisis. Due to the Arab oil embargo in 1973, the Energy Research & Development Administration (now the Department of Energy) was created to help the US become self-sufficient in energy (Strum 1983; US Department of Energy 2020). This energy crisis also drove the creation of the Solar Energy Research Institute (now the National Renewable Energy Laboratory) to increase energy security and reduce dependence on foreign oil (Strum 1983; US Department of Energy 2016). However, instead of waiting on a crisis to arrive, the US could instead increase its research, development, and deployment of NETs now to begin reducing climate change effects immediately.

Reframing the climate change problem also requires a consistent story among all climate change mitigation supporters. Many supporters are very much against implementing NETs, especially because they are associated with geoengineering and contribute to the moral hazard narrative. For example, although Bernie Sanders supports the ambitious Green New Deal, he also says that "to get to our goal of 100 percent sustainable energy, we will not rely on any false solutions like nuclear, geoengineering, carbon capture and sequestration, or trash incinerators" (Sanders 2020). Calling geoengineering a false solution while IPCC research explicitly shows the need for geoengineering solutions like BECCS to stay below 1.5°C of global warming again reveals the gap between science and policy. This kind of political framing is detrimental to adequately combating climate change.

This dissertation reveals that more should and can be done to manage the concentration of CO_2 in the atmosphere rather than only focusing on new emissions created daily. US policies under the Clean Air Act, popular emissions trading schemes, and carbon capture and storage technologies are not addressing this issue. Using NETs is the only option to achieving net negative emissions. This research encourages using NETs to mobilize policy around a new carbon management strategy by focusing on the science of carbon mitigation rather than cost effectiveness. This dissertation provides insight for future environmental policy design and climate change governance, informing how NETs, specifically DAC, can be incorporated into policy as a complement to other CO_2 mitigation strategies in order to get to the root of the climate change problem.

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BIOGRAPHICAL SKETCH

Evvan Victoria Morton was born in Cincinnati, Ohio. She received her Bachelor's degree in Materials Engineering from the University of Cincinnati and her Master's degree in Sustainable Engineering from Arizona State University (ASU). She received a two-year IGERT-SUN Fellowship from the National Science Foundation to pursue her doctoral degree in Sustainable Engineering at ASU while also pursuing a certificate in Responsible Innovation in Science, Engineering, and Society. While at ASU, Evvan served as the President of Black Graduate Student Association, Climate Change Task Force Lead for the Arizona Science Policy Network, a member of the university Committee for Campus Inclusion, and received the 2018 Martin Luther King Jr. Student Servant-Leadership Award. She also co-founded BioGals, a non-profit organization that empowers women of color in science, technology, engineering, and math through study abroad experiences. Motivated to bridge the gap between science and decision-making, Evvan looks forward to a career in science policy to develop innovative policies for transitioning to a sustainable energy future.