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Maximum Carbon Dioxide Capture, Sequestration And Maximum Carbon Dioxide Beneficial Reuse At The Optimal Cost Efficiency For The Power Generation Sector To Address Global Temperature Rise

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Maximum Carbon Dioxide Capture, Sequestration and Maximum Carbon Dioxide Beneficial Reuse at the Optimal Cost Efficiency for the Power Generation Sector to Address Global Temperature Rise

by

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A Dissertation
Submitted to the Graduate Faculty

of the

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In partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

Grand Forks, North Dakota

May 2021

This dissertation submitted by Michael Dean Garcia, P.E., CSP in partial fulfillment of the requirements for the Degree of Doctor of Philosophy Environmental Engineering from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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Associate Dean of the School of Graduate Studies

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PERMISSION

Title	Maximum Carbon Dioxide Capture, Sequestration and Maximum Carbon Dioxide Beneficial Reuse at the Optimal Cost Efficiency for the Power Generation Sector to Address Global Temperature Rise
Department	Environmental Engineering
Degree	Doctor of Philosophy

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Michael Dean Garcia, P.E., CSP
May 2021

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To my wife Sonia Y. Garcia, my children Marina, Aryana and Michael Garcia for their support and patience. Also to my mom Maria R. Garcia and my brother Joseph J. Garcia, PhD

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ABSTRACT

Global Climate Change is arguably one of the most important global crises of our times. Global Climate Change is the result of increasing global ambient temperatures around the world. These increased temperature changes have been impacting all aspects of human life and activity as wells as impacting all biological and physical systems of Earth. The primary cause of Global Climate Change are anthropogenic emissions of carbon dioxide and other Greenhouse Gases. Fossil fuel combustion is a primary source of these emissions. The initiation of anthropogenic Global Climate Change has been scientifically traced back to the Industrial Revolution. From the Industrial Revolution to current times, Greenhouse Gas emissions from the burning of fossil fuels have steadily increased. The current carbon dioxide average recorded concentrations are the highest concentrations ever identified over the past 800,000 years.

There are significant effects associated with Climate Change and global average temperature rise. Some of these effects include rising sea levels, the melting of the polar ice caps, reduction in the polar and hemispheric albedo, higher global temperatures, increased range of disease caring vectors, increased droughts, increased severe weather, effects on crop production and wildlife biological effects. These negative Global Climate Change effects will disproportionately affect the most economically disadvantaged and most vulnerable populations of the world.

There are a number of Greenhouse Gases that are associated with Global Climate Change; however, carbon dioxide has been proven to be the most significant. One of the largest sources of anthropogenic carbon dioxide emissions is from the electrical power generation sector. From this sector, coal-fired power generation plants emit the most carbon dioxide, followed by natural gas-fired power generation plants.

Climate Change is an extremely complex global challenge. As a complex global challenge, addressing this issue will require a number of complex and collaborative solutions, from many experts, from a number of scientific and professional fields. This dissertation addresses only one specific aspect of the Global Climate Change challenge.

This dissertation addresses carbon dioxide capture, sequestration and beneficial reuse for the electrical power generation sector. Specifically, the dissertation evaluates the primary carbon dioxide capture technologies in order to maximize carbon dioxide capture, sequestration and beneficial reuse at optimum cost efficiencies for fossil fuel-fired electric generating power plants. An algorithm has been developed as part of the dissertation that addresses the most critical variables to maximize carbon capture from coal-fired and natural gas-fired power plants while maximizing beneficial carbon dioxide reuse, both at the most efficient economic value.

The dissertation contains three examples of the algorithm in use for three different regions of the world. The dissertation also presents an implementation strategy to capture carbon dioxide from fossil-fueled electric generation plants. The total reduction in carbon dioxide sequestration from the global fossil-fueled power generation sector could be approximately 31% of the total global anthropogenic emissions if all fossil-fired plants employ carbon dioxide capture. Results from this dissertation can be replicated and used to estimate the reduction of carbon dioxide emissions from other major global carbon dioxide emissions sectors.

CHAPTER 1: INTRODUCTION TO CLIMATE CHANGE

1.1 Background and Motivation

As a young man, I have always been fascinated with math and science and I have specifically been interested in the environmental sciences. My studies and my career initiated in the environmental engineering field and continue in the environmental engineering field to this day. My early career focused on environmental compliance and pollution mitigation and slowly evolved into pollution prevention, resource recovery, recycling, Climate Change and Sustainability. I can recall these topics beginning to be significant items in my life in the early 1990s during my undergraduate studies and course work. I have worked for twenty-five (25) years in the environmental engineering field and I have dedicated my life to improve the environment, my surroundings and improving the environmental performance of the companies and organizations that I have worked for. I have worked tirelessly my entire career on sustainable manufacturing and sustainable development in industry and higher education.

The motivation for this dissertation is my desire to positively contribute to the improvement of the Global Climate Change challenge. As I will explain in detail later in the dissertation, Global Climate Change is one of the most critical global challenges of our lifetime. This is a critical global issue that has the potential to affect all humans and all life forms on Earth. So my desire is to use my experience, expertise and knowledge to help address Climate Change and to improve the condition of our planet for my children and future generations.

1.2 Research Objectives

The primary objective of this dissertation is to develop an algorithm that can be used to evaluate carbon capture technology options that are focused on maximizing carbon dioxide emission capture from the power generation industry while maximizing the beneficial carbon dioxide reuse, both at the optimal cost efficiency. The global fossil fuel-fired power generation sector is the single highest carbon dioxide emitting sector. This algorithm can be used to prioritize the implementation of carbon dioxide capture and beneficial reuse, based on the global fossil fuel-fired power generation emissions. The algorithm can also be replicated and can be used to reduce or eliminate carbon dioxide emissions from other significant carbon dioxide sources.

The general dissertation questions are: 1) Which sector is the primary source of global carbon dioxide emissions? 2) What are the most cost-effective emissions abatement or capture technologies for these emissions? and, 3) How can these captured carbon dioxide emissions be beneficially used by society? More specifically, the dissertation will focus on carbon dioxide capture and reuse from fossil fuel-fired generating power plants, as these are the primary emitters of carbon dioxide in the power generation sector.

In this dissertation, the primary Global Climate Change causes and sustainable/economical mitigations will be identified. The dissertation will:

- Develop a synopsis of the historical and current status of the Global Climate Change crisis.
- Determine the primary causes of Global Climate Change based upon the IPCC reports and additional scientifically peer-reviewed sources.
- Determine the primary causes/sources and the global locations of these sources.

- Determine the primary inventory of Global Climate Change carbon dioxide sources from this data.
- Describe and detail the primary implications and detrimental impacts of Global Climate Change.
- Determine a number of feasible, sustainable and economically viable carbon dioxide capture/sequestration/mitigation techniques and technologies.
- Determine a number of beneficial uses of the captured or mitigated carbon dioxide.
- Propose a prioritized synopsis (algorithm) for the implementation of these critical mitigation options.

A primary objective will be to develop an algorithm to assist in the selection of carbon capture, sequestration, and reuse options:

- Determine carbon dioxide emissions sources and location/geography. Coal-fired and natural gas-fired power plants apply to this algorithm. (Primarily focused on Coal and Natural Gas Power Plants).
- Determine the most feasible carbon dioxide capture method based on location and availability of the technology (List of viable capture technologies).
- Determine the most beneficial carbon dioxide re-use based on availability and location/geography.
- Economic review: Optimization of implementation, based on capture technology (availability, feasibility and economics) and available beneficial re-use based on location/geography.

- The algorithmic outcome will be the most feasible and economic carbon dioxide capture technology with the most effective and efficient carbon dioxide re-use for coal and natural gas-fired power plants.

1.3 Introduction to Climate Change

Global Climate Change is arguably one of the most significant world crises currently affecting humanity, the Earth and all life forms on the planet. Global Climate Change is a result of the rising average atmospheric ambient temperatures of the Earth. Global Climate Change is primarily caused by the atmospheric insulating effect caused, in part, by the collection of fossil fuel-burning gases emitted into the atmosphere. The Earth’s troposphere or lowest atmospheric level is the part of the atmosphere affected by fossil fuel emissions or Climate Change. Since the Industrial Revolution, historical and scientific data has demonstrated that Global Climate Change gases have exponentially increased. The primary Climate Change gases of concern include carbon dioxide, methane, nitrous oxide and water vapor. Of these primary Climate Change gases, carbon dioxide has been determined to be one of the most significant due to its relatively high concentration in the atmosphere. Scientists around the globe have determined that carbon dioxide has the most significant effects on the Global Climate Change crisis (Bex 2013; Climate Change 2014; Crimmins 2016; Parry 2007).

The anthropogenic Climate Change gases are of the most concern due to the significant increases in these levels since the Industrial Revolution. Atmospheric carbon dioxide emissions levels have significantly increased since the largest onset of fossil fuel usage and continues to climb. The significant effects of Climate Change have and will continue to affect all parts of the globe and all aspects of human life. The significant effects of Global Climate Change have and will continue to have a tremendous negative effect on the most vulnerable and impoverished populations of the world. All humanity will potentially be affected, however the most underprivileged and most vulnerable will be the most affected by the impacts of Climate Change (Parry 2007; Sachs 2008; Sachs 2015).

The continuing increases in anthropogenic emissions from fossil fuel consumption will continue to cause the global ambient temperatures to rise. In October of 2018, The International Panel on Climate Change submitted to the United Nations and released a special report: Special Report on Global Warming of 1.5^{o}C. The report explains that Global Warning to at least 1.5^{o}C above pre-industrial levels is likely to occur between 2030 and 2052. The report goes on to explain the negative climatic and biological consequences from the likely rise in global temperatures. The report states that in order to limit Global Warming to 1.5^{o}C or below, the world's net carbon dioxide emissions would need to be cut by approximately 45% by 2030 and reach a net zero by 2050. The report states that limiting Global Warming to 2.0^{o}C would require carbon dioxide emissions to be reduced by 25% by 2030 and 100% by 2075. There are a number of potential effects of Climate Change, several that are already being observed. Some of the primary effects include extreme weather events, melting of glaciers, changes in seasonal event timing, changes in agricultural productivity, sea level rise and the shrinking of the polar sea ice caps. All of these changes will have direct, cascading and cyclical effects on the processes and biological systems of Earth (Masson-Delmotte 2018).

Figure 1.1 below shows the observed mean, modeled and projected Global Mean Surface Temperature changes (rise) from 1840 to 2030. This graph illustrates the mean surface temperature rise caused primarily by carbon dioxide emissions from the burning of fossil fuels and indicates the Global Climate Change effects starting from the Industrial Revolution (Masson-Delmotte 2018).

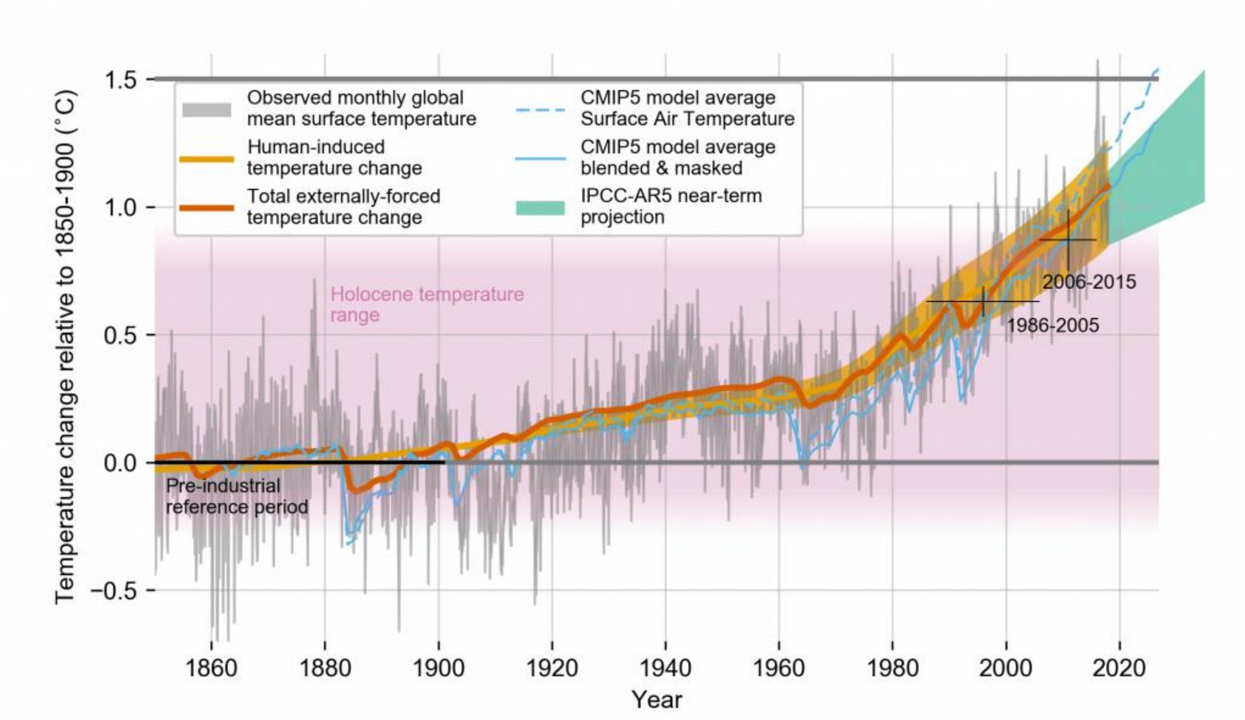


Figure 1.1: Evolution of global mean surface temperature (GMST) over the period of instrumental observations (Masson-Delmotte 2018).

CHAPTER 2: BACKGROUND

2.1 Greenhouse Gases and Their Link to Climate Change

This section provides a summary of Greenhouse Gases and how they contribute to Global Climate Change. To begin with, some of the energy from the Sun is absorbed by the Earth and some is reflected back into space. The balance between the incoming and reflected solar energy determines the surface temperature of Earth. Greenhouse Gases are gaseous compounds that are in the Earth's atmosphere that absorb infrared radiant energy from the Sun and trap heat in the lower atmosphere as part of the energy balance. The presence of these gases helps maintain the Earth's temperatures at a habitable level. When the concentrations of Greenhouse Gases increase, more heat is trapped in the Earth's lower atmosphere, this leads to Climate Change or Global Warming. Greenhouse Gases can be naturally occurring or anthropogenic. Significant and recent increases in anthropogenic or manmade Greenhouse Gases has been a primary contributor to the global average ambient temperature rise (Schneidemesser 2015; Letcher 2016; Pachauri 2014).

The primary Greenhouse Gases of concern for Climate Change are water vapor, carbon dioxide, methane and nitrous oxide. Because of its higher concentrations and abundance in the atmosphere, carbon dioxide has a significant effect on Climate Change. Carbon dioxide also remains in the Earth's atmosphere for up to thousands of years. Methane is more than twenty times more heat absorbent than carbon dioxide. However, methane is less abundant in the atmosphere and only remains in the atmosphere for about ten to twelve years. Water vapor is the most abundant Greenhouse Gas in Earth's atmosphere, however, water vapor only remains in the atmosphere for days (Schneidemesser 2015; Letcher 2016; Pachauri 2014).

The Greenhouse Gases absorb the Sun's energy by the bending and vibrating of the molecular bonds of the gas compounds. When Greenhouse Gas molecules absorb infrared radiation, they vibrate which causes the air around them to warm. Then the Greenhouse Gases release the infrared radiation in all directions and some can be released back toward the surface of the Earth. The surrounding Greenhouse Gas molecules can then absorb the infrared radiation again causing the molecules to vibrate and warm more of the surrounding air. This continuing molecular infrared radiation absorption contains the heat in the lower atmosphere and the surface of the Earth. The absorption and re-emitting of infrared radiation energy make Greenhouse Gases effective heat-trapping gases. At a molecular level, methane, because of its physical and chemical composition absorbs more infrared radiation than carbon dioxide. A methane molecule has more vibrational degrees of freedom that are infrared activated and therefore has a higher heat capacity than a carbon dioxide molecule. Methane is a more powerful heat-absorbing Greenhouse Gas than carbon dioxide, however, there is more carbon dioxide in the lower atmosphere and based on recent data, carbon dioxide concentrations in the lower atmosphere are increasing more rapidly than other Greenhouse Gases. Figure 2.1 illustrates the Greenhouse Effect and shows how solar energy is absorbed, reflected and absorbed by Greenhouse Gases (Schneidemesser 2015; Letcher 2016; Pachauri 2014).

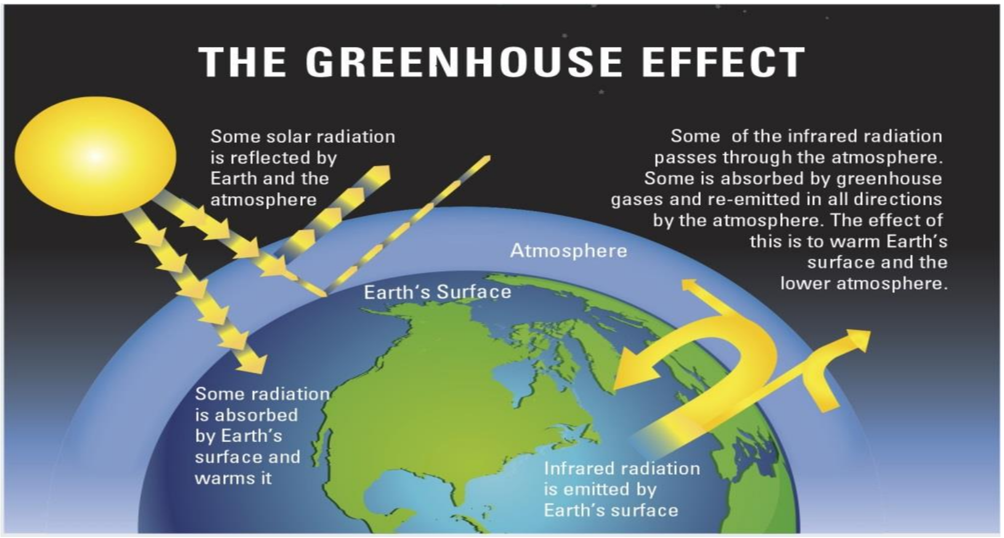


Figure 2.1 Illustration of the Greenhouse Effect (The Basics of Climate Change 2020).

2.2 Brief History of Climate Change

The modern Global Climate Change crisis has been extensively researched and scientifically tracked back to the Industrial Revolution. In 1712 the first steam engine was invented and this is arguably the start of the Industrial Revolution and the start of Global Climate Change. The Industrial Revolution had its origins in Britain during the 1700s. Many historians bracket the Industrial Revolution from about 1760 to approximately 1840. During this period, there was a significant shift in manufacturing from manual manufacturing to more mechanized manufacturing processes (Mgbemene 2011; Whyte 2013; Fay 2012).

During the Industrial Revolution, the increased mechanized manufacturing was fueled by increased utilization of fossil fuels which in turn increased the pollution in major cities in Britain and the United States. This included a significant increase in the consumption of fossil fuels, at first primarily for steam generation. Specifically, coal and the burning of coal as a fuel for steam engines are the origins of the widespread air pollution and Climate Change issues around the world (Mgbemene 2011; Whyte 2013; Fay 2012).

The Industrial Revolution was contained to England for the first fifty (50) years but soon spread throughout Europe and to the US. The primary growth of the Industrial Revolution included mechanization of manufacturing and the mechanization of transportation with the rise of steam engines for ships and trains. The significant increases in fossil fuel usage as part of the Industrial Revolution directly began the increased emissions of Climate Change gases and carbon dioxide is the most significant of these gases (Mgbemene 2011; Whyte 2013; Fay 2012).

By 1895, some scientists were researching and were concerned about the possible increases in carbon dioxide emissions and the effects for the potential for Global Warming. In the 1930's Guy Stewart Callendar had noted that the US and North Atlantic regions of the world had had significant warming after the Industrial Revolution (Mgbemene 2011; Whyte 2013; Fay 2012).

In the late 1950s, Charles Keeling was measuring the changing atmospheric carbon dioxide levels from Hawaii's Mauna Loa Observatory. Keeling's data showed a steady rise in carbon dioxide levels. So scientists and the scientific community have been concerned about Climate Change and increased carbon dioxide emissions for more than 60 years. Figure 2.1 is the Atmospheric CO_2 steady increase from 1960 to 2020. (Scripps 2013).

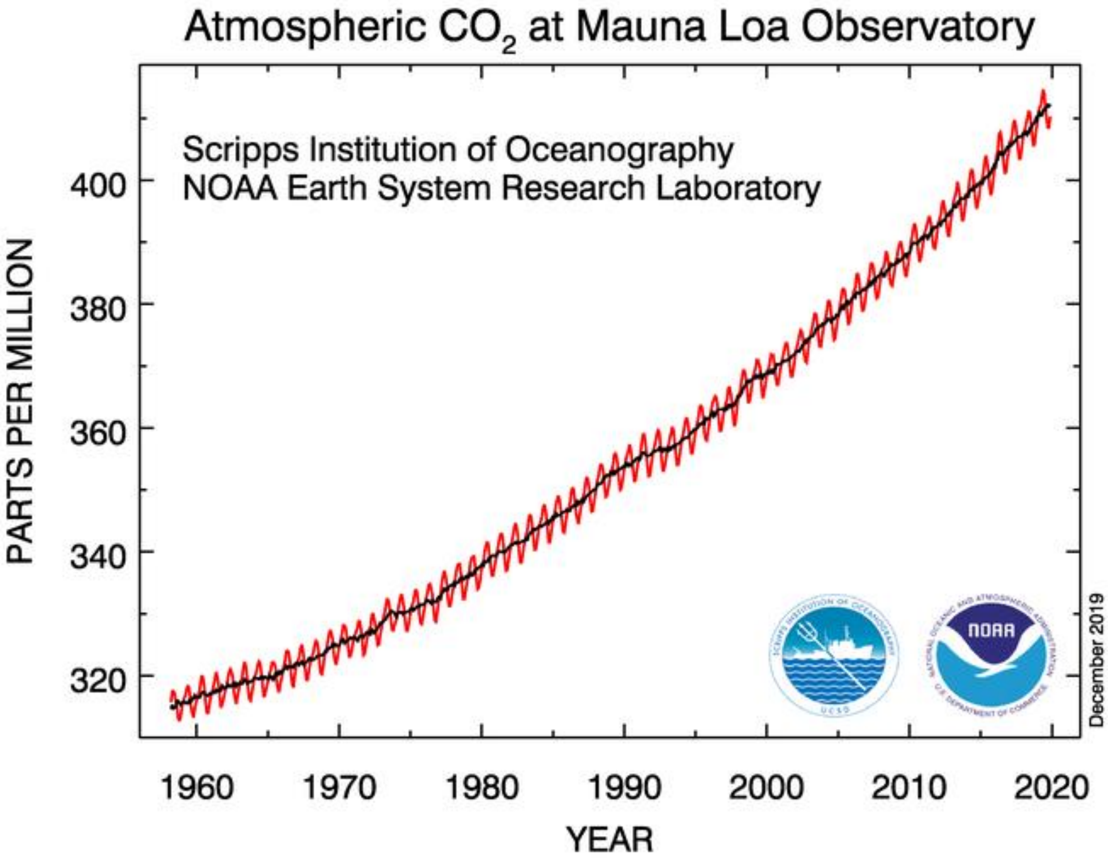


Figure 2.2: Mauna Loa Observatory Atmospheric CO_2 Concentrations 1960 – 2020. (NOAA Earth Systems Research Laboratory, Mauna Loa, Hawaii Observatory).

2.3 Current Status of Climate Change Crisis

As of December 13, 2019, the average global carbon dioxide concentration was 412 ppm. The all-time high record for average daily carbon dioxide was May 15, 2019, at 416 ppm. The global average carbon dioxide levels at this time are higher than at any other point in time in the last 800,000 years. This is based on paleoclimatological analyses such as polar ice cap core sampling analytical results. The average global carbon dioxide levels have had a steadily trending increase since the initiation of the measurements in 1958 (Figure 2.3.1)(Scripps 2013; Masson-Delmotte 2018).

Current average atmospheric carbon dioxide levels are trending upward and are at all-time highs. There has been approximately a 1.0^{o}C of Global Warming since pre-industrial times. The current average sea level rise since 1880 is approximately 8 inches and is currently 0.13 inches per year. Increased global ambient temperatures will accelerate sea level rise and a number of additional detrimental Climate Change effects. There are millions of people that are living through the effects of Global Climate Change. There are approximately 200 million people on Earth that live in and around the coastal regions of Earth. If Global Climate Change continues to increase sea level rise, it is estimated that 100 million people could be displaced by sea level rise by the end of the century (Masson-Delmotte 2018; Parry 2007).

There are a number of potential detrimental effects as a result of Global Climate Change. Many of the effects have been occurring for years and will continue to be exacerbated. Some of these issues include the rise in average ocean and surface temperatures, the melting of the polar ice caps, significant increases in snowmelt, the melting of glaciers, sea level rise around the world, increased severe weather events, increases in droughts, water scarcity and security issues, increased loss in worldwide agricultural production, ocean acidification, increases in vector borne diseases, increases in pandemic outbreaks, displacement of millions of coast residents around the world, the disappearance of island nations, significant changes in weather patterns, changes in the Earth’s physical cycles and the potential extinction of many biological species (Crimmins 2016; Fay 2012; Masson-Delmotte 2018; Melillo 2014; Parry 2007).

2.4 Primary Causes of Climate Change

There are a number of factors that contribute to Global Climate Change. While there are several natural occurrences of Greenhouse Gases such as changes in the Sun’s intensity, volcanic activity and eruptions, and changes in the natural emissions of Greenhouse Gases; paleoclimatological data in the form of ice core analysis from the Earth's polar regions, tree ring analysis, coral analysis, and ocean and lake sediment analysis have yielded scientific evidence that the most recent increases in average global temperature rise can be traced back to the Industrial Revolution. The most significant events that began to occur in the Industrial Revolution included a significant increase in the usage of fossil fuels to mechanized manufacturing and transportation throughout the world. Historical records and eyewitness accounts have documented the increased levels of airborne pollutants in 18th century Europe and the United States (Jouzel 2013; Geerts 2020).

The scientific evidence has strongly concluded that the Industrial Revolution was a potential genesis of the modern-day Global Climate Change crisis. The primary fuel used to power the Industrial Revolution was coal followed closely behind by petroleum based products. Figure 2.4.1 consists of ice core carbon dioxide analysis results from Antarctica and Greenland. The data set illustrates the modern increase in carbon dioxide atmospheric concentrations starting in the late 1700s and early 1800s, the time of the Industrial Revolution (Jouzel 2013; Geerts 2020; Whyte 2013; Fay 2012).

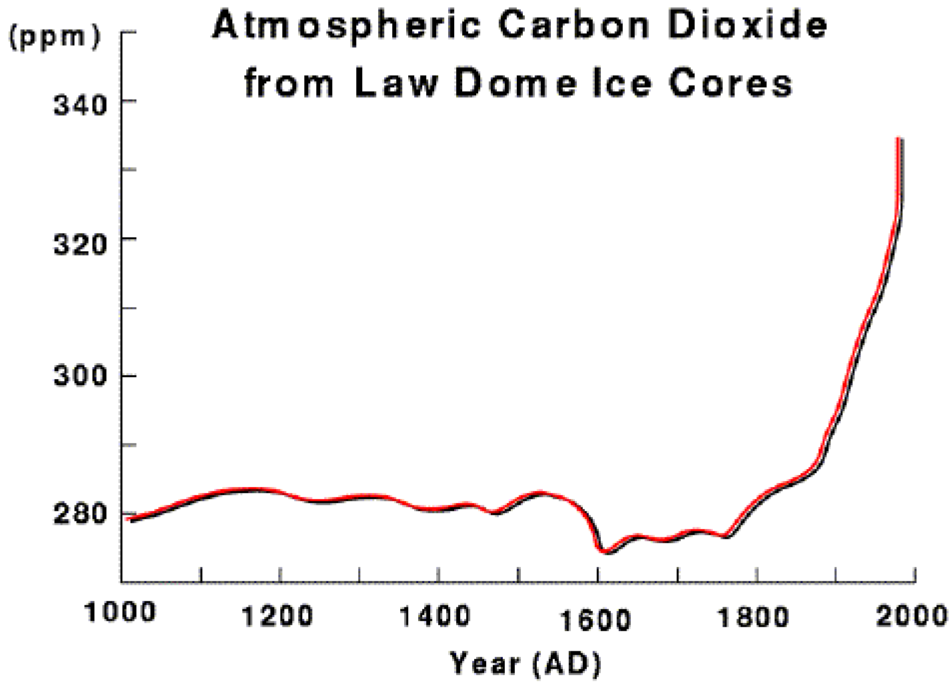


Figure 2.4.1: Average air bubble CO_2 concentration versus age in three ice cores taken close to the summit of Law Dome, around 1390 m elevation. Law Dome is near the Australian station Casey. (Geerts 2020).

Since the late 1700s, coal was the primary fossil fuel source for industry and electrical generation. In more modern times coal usage has been slightly reduced in the developed countries of the world, but not the developing countries of the world. Natural gas has become the primary fuel source for electrical power generation in many parts of the world. At this time, most countries on Earth are still primarily using fossil fuels to fuel their societies and economies. Fossil fuels are the dominant power source in most parts of the world in one form or another. There are parts of the world that have slowly transitioned into more renewable energy societies (Dow 2011; Electrical 2018; Fay 2012; Oliver 2016; Whyte 2013).

Fossil fuels are used in all aspects of human activities and civil society. Gasoline or any of a number of other oil-based fuels are the primary automobile and transportation fuel sources around the world. On a global basis, carbon dioxide is the most significant Greenhouse Gas for two distinct reasons. The first is the relatively high concentration of carbon dioxide in the atmosphere compared to the other Greenhouse Gases, except for water vapor. Also, the significant increase in carbon dioxide concentrations in the atmosphere since the Industrial Revolution (Bex 2013; Blunden 2018; Fay 2012; Panchauri 2015; Ritchie 2018; Solomon 2007).

Based on Global Climate Change emissions inventories, paleoclimatological data and research of the Greenhouse Gases, carbon dioxide is the most significant and the most concerning. From the IPCC 2014 report, for 2010 carbon dioxide was 65% of the global Greenhouse Gas emissions. By far the most significant emissions by volume are global carbon dioxide emissions, 25% were from electrical production and heat production. Based on my research and a review of existing peer-reviewed data, I have concluded, as well as many others, that carbon dioxide emissions are the most significant emissions causing Global Climate Change. Because of these factors, I have decided to focus my dissertation on fossil fuel carbon dioxide emissions and specifically power generation carbon dioxide emissions (Geerts 2020; Jouzel 2013; Panchauri 2015; Solomon 2007).

Figure 2.4.2 below shows the significance of carbon dioxide emissions in relation to other greenhouse gas emissions (Climate Change Indicators 2014).

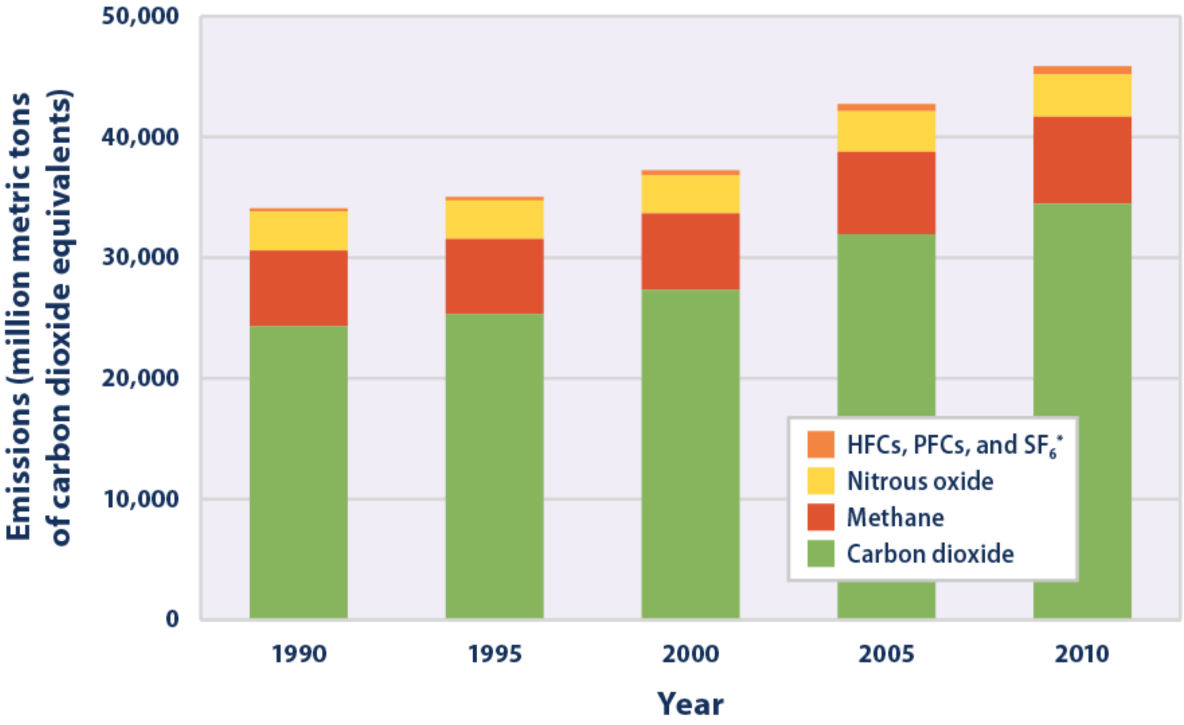


Figure 2.4.2: Worldwide emissions of carbon dioxide, methane, nitrous oxide, and several fluorinated gases from 1990 to 2010 (Climate Change Indicators 2014).

Figure 2.4.3 below shows the global carbon dioxide emissions from 1850 to 2019 and the projected carbon dioxide emission from 2019 to 2040 (Global Emissions).

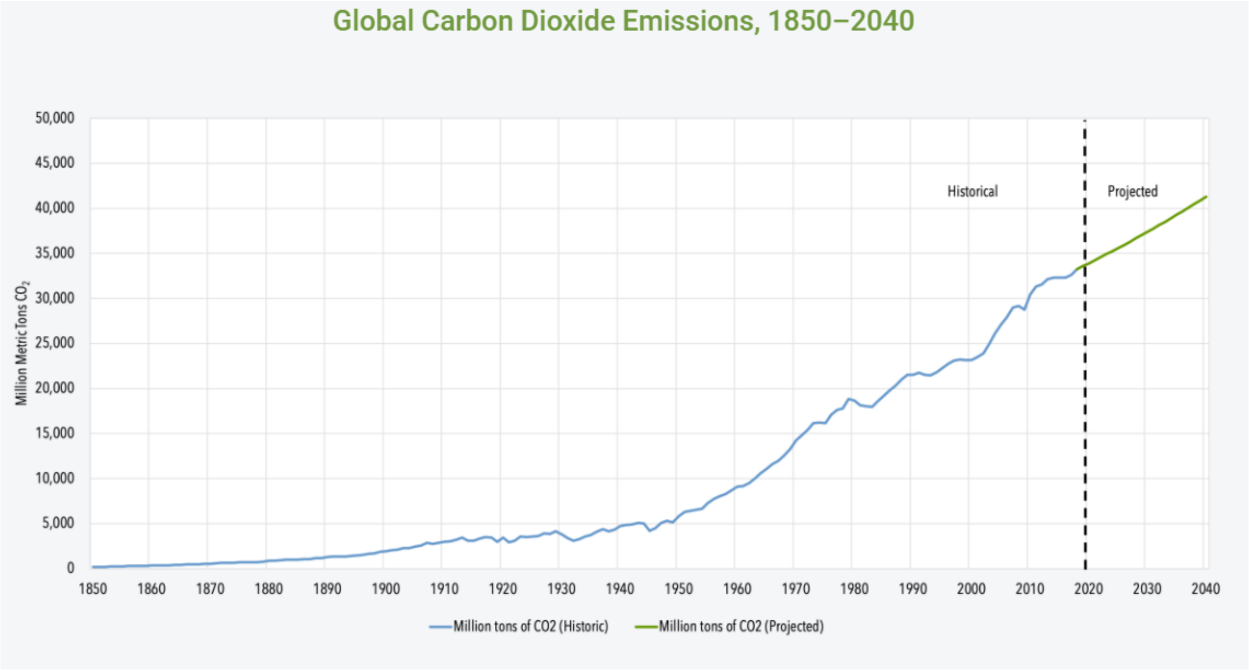


Figure 2.4.3: Global Carbon Dioxide Emission, 1850 – 2040 (Global Emissions).

2.5 Primary Causes/Sources and Their Global Locations

The combustion of fossil fuels around the world is a primary contributor to Climate Change. The primary global sectors that cause carbon dioxide emissions are the electricity and heat production sector, the transportation sector, the manufacturing & construction sector, the other fuel combustion sector and the fugitive emissions category. Based on the IPCC 2014 Climate Change Mitigation of Climate Change report, the energy and transportation sectors' carbon dioxide emissions are projected to double by 2050. Based on my review of the power generation sector carbon dioxide emissions inventory, I have concluded that the global carbon dioxide emissions from the power generation sources are some of the most significant emissions contributing to Global Climate Change. From this inventory, I have found that China is the leading emitter of carbon dioxide and the US is second. In 2014, it is estimated that China emitted 30.19% of the world’s carbon dioxide and the US emitted approximately 15.45% of the world's carbon dioxide. Together China and the US emit more than 45.5% of the carbon dioxide emissions globally. The top 20 carbon dioxide emitting countries of the world emitted approximately 81.64% of the Earth's manmade carbon dioxide emissions (Highest Emitting Nations 2014; Pachauri 2014; Climate Change 2014).

The top three carbon dioxide emitters for 2014 were China, the USA and India. This data is for fossil fuel burning, cement production and gas flaring. Therefore, based on the 2010 global carbon dioxide emissions inventory, electrical power generation is the highest emitter of global carbon dioxide gases. Figure 2.5.1 illustrates the global Greenhouse Gas emissions by gas and shows the significance of carbon dioxide emission. So this dissertation is focused on electrical power generation carbon dioxide emissions. The primary fuel sources for these emissions sources are coal-fired power generation plants and natural gas-fired power generation plants. Coal-fired power generation plants emit 40% to 50% more carbon dioxide than natural gas-fired power generation plants (Highest Emitting Nations 2014; Carbon Capture Handbook 2015; Carbon Dioxide Uncontrolled Emissions Factors 2016).

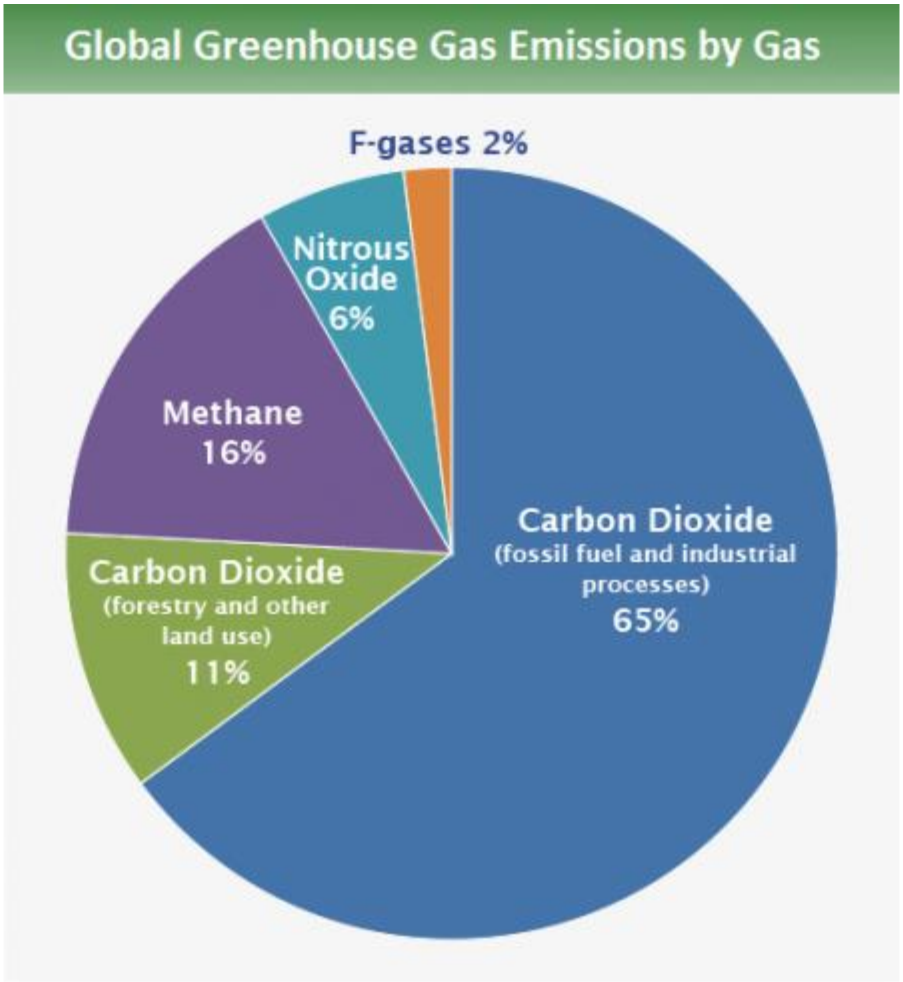


Figure 2.5.1: Global Greenhouse Gas Emissions by Gas 2014 (Global Greenhouse Gas Emissions Data 2020).

The IPCC 2014 Climate Change Synthesis Report was reviewed. In the report, there are global anthropogenic carbon dioxide emissions from 1850 to 2010 from fossil fuel combustion, cement production and flaring (Figure 2.4.2). There are also total annual anthropogenic Greenhouse emissions by gases from 1970 to 2010 (Figure 2.5.3). The report has a Greenhouse Gas emissions chart by economic sectors for 2010. From these inventories, charts and graphs it is evident that carbon dioxide emissions from the electricity and heat production sector are the most significant global carbon dioxide emissions (Pachauri 2015; Oliver 2016).

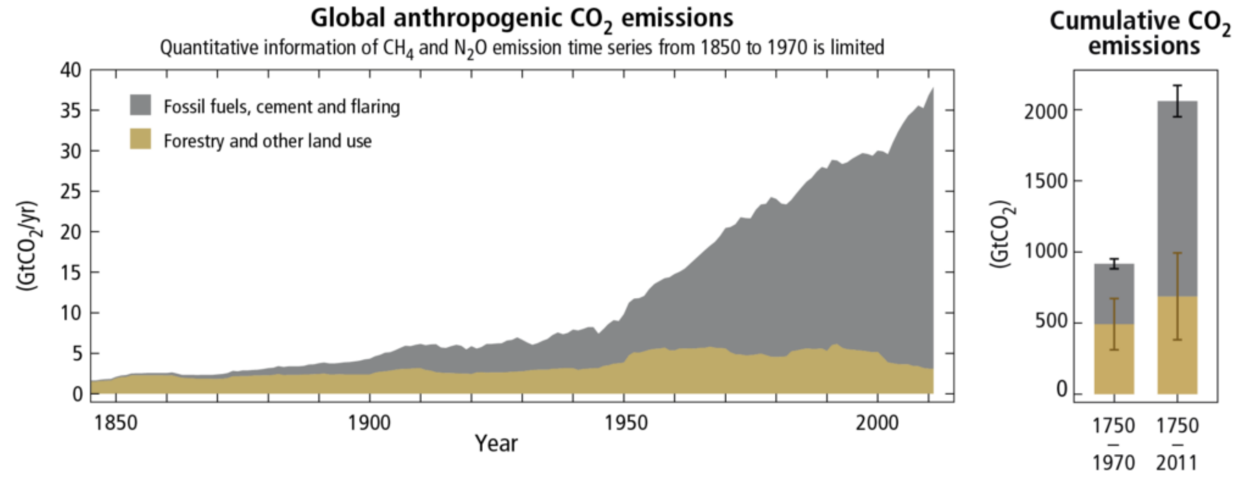


Figure 2.5.2: Global anthropogenic CO$_2$ emissions (Pachauri 2015).

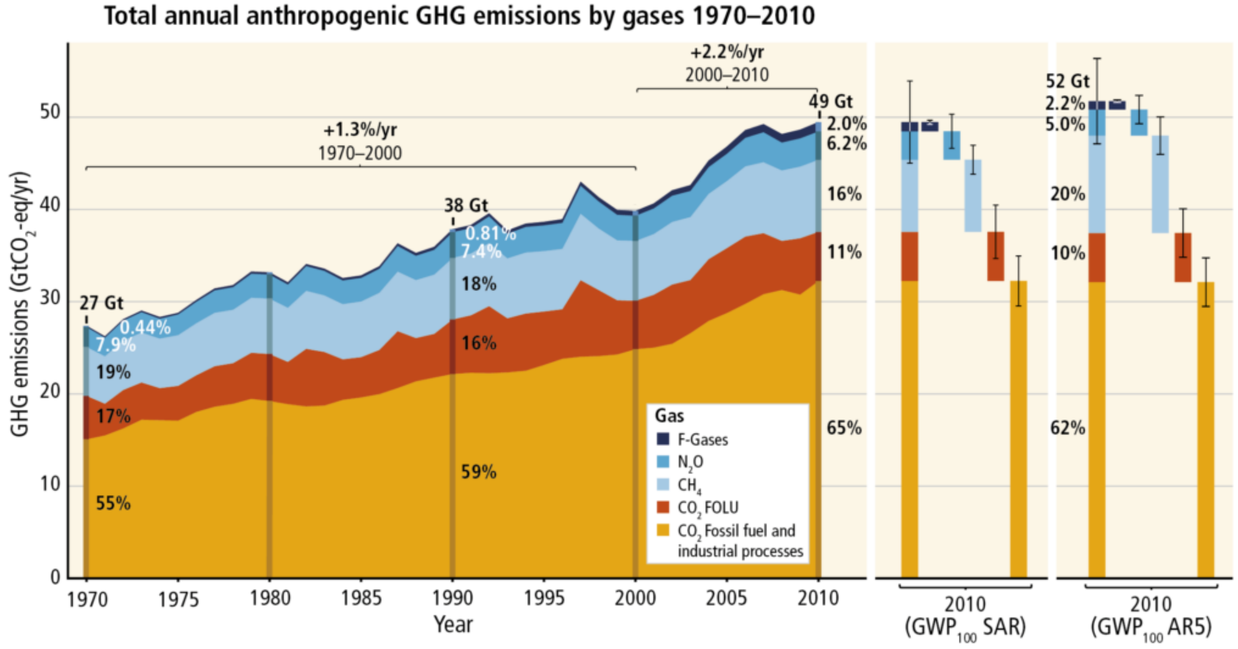
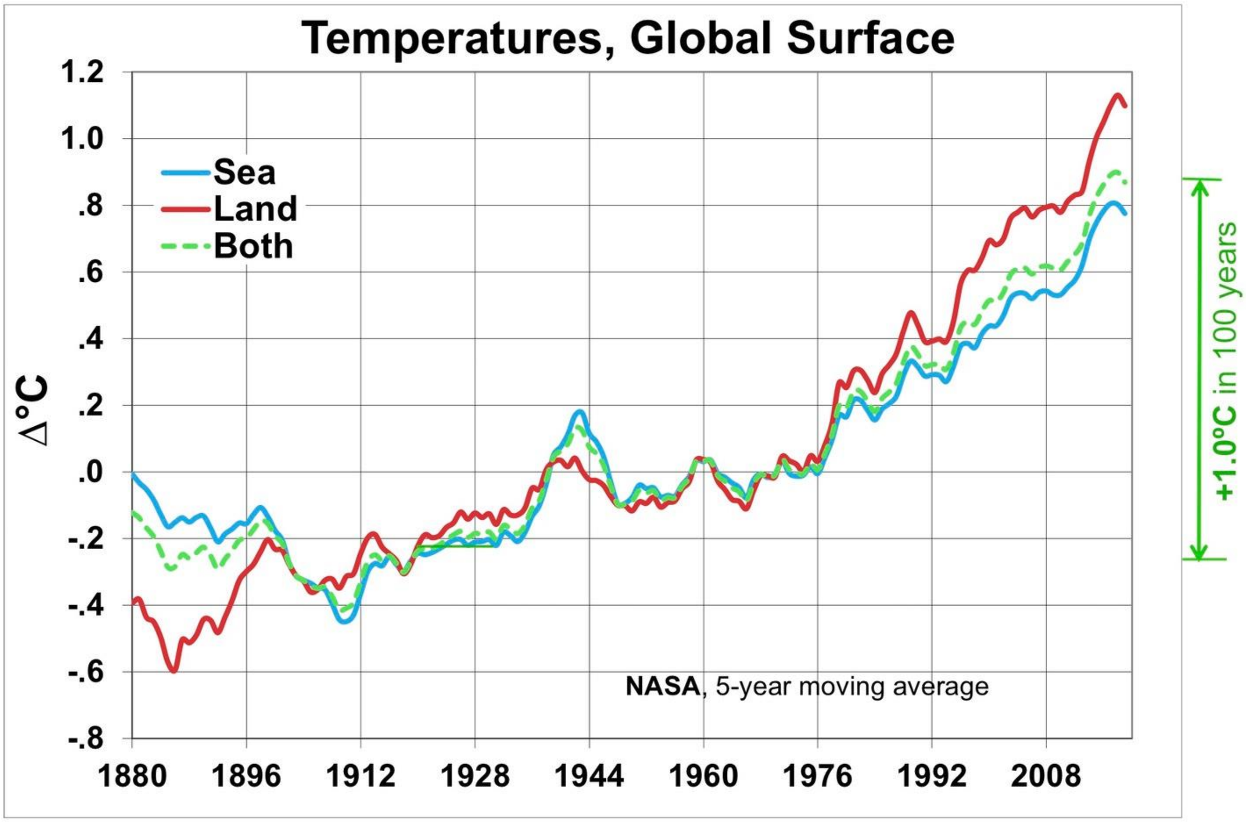


Figure 2.5.3: Total annual anthropogenic GHG emissions by gases 1970-2010 (Pachauri 2015).

2.6 Primary Implications and Detrimental Effects of Global Climate Change

There are a number of detrimental effects that can be attributed to Global Climate Change. Global Climate Change or Global Warming is the critical crisis in which the Earth’s average ambient temperature is slowly but certainly rising and is primarily caused by the burning of fossil fuels. Figure 2.5 illustrates the average ambient temperature increases for the last 136 years, from 1880 to 2016. There is scientific evidence that average ambient temperature rise has been occurring at an alarming rate for both the ocean temperatures and surface land temperatures (Global Climate Change 2020).



The 1998-2018 rate of change is
2.5°C / 100 years for Land,
2.0 for Sea,
2.1 for Both.

At that rate, “Both”
will pass 2°C above 1880 levels in 2079.
“Land” in 2040.

Figure 2.6: Global Land and Sea temperature rise 1880-2010 (Global Climate Change 2020).

There are a number of detrimental effects that have occurred and continue to occur due to the rising average ambient ocean and land temperatures. Some of these effects as listed in Table 1, include reductions in ice caps/glaciers and increased snowmelt, sea level rise, island nations succumbing to seas level rise, global coastal regions succumbing to sea level rise, regional climatic changes, increased vector carried diseases, increased and more severe pandemics, increased severe weather and severe weather events, increased and more severe wildland fires, more severe and frequent droughts, water shortages, crop losses, increased famine, coral reef bleaching, marine animal extinctions, possible species extinctions and increased human death rates. The most vulnerable species on Earth and the most vulnerable humans will experience the effects of Climate Change first and the most. Sea level rise could affect 200 million people around the world due to Climate Change in the next 80 years. The more than 700 million people that live in poverty in the world would be some of the most affected by Climate Change (Global Climate Change 2020; Draft Climate Science Special Report 2015; Fay 2012; Masson-Delmotte 2018).

Table 1: Summary List of Climate Change Effects.

1. Polar Icecap Thinning and Melting	11. Increased and more severe droughts
2. Glacier Detraction	12. Increases in water shortages
3. Increased Snowmelt	13. More frequent crop losses
4. Sea Level Rise	14. Increased famine
5. Regional climate changes, Widening Tropics	15. Coral reef bleaching
6. Ocean Current Changes	16. Marine animal extinctions
7. Ocean Acidification	17. Animal extinctions
8. Increase vectors, diseases and pandemics	18. Human population displacement
9. Increased frequency of severe weather events	19. Increased rate of human deaths

10. Increased and more severe wildland fires	

While there are a number of potential detrimental effects that are attributed to Global Climate Change, sea level rise is one of the most detrimental effects of Climate Change. Sea level rise is the direct effect of the thinning and melting of the Polar ice sheets and Polar ice caps, glacier detractions and increased snowmelt. All of these observed impacts are directly caused by the increases in ambient and ocean water temperatures. These impacts also affect marine animal life, ocean cycles, ocean currents, marine biology, regional and global weather patterns and ocean chemistry. Sea level rise will potentially displace 200 million people around the world (Global Climate Change 2020; Draft Climate Science Special Report 2015; Fay 2012; Masson-Delmotte 2018; Letcher 2016).

In recent years we have also seen the increased frequency of severe and extreme pandemics, weather events and natural disasters, including more frequent and more intense hurricanes, typhoons and tropical storms. The world has also seen more severe and more intense wildland fires, flooding, droughts and water shortages. This has contributed to crop losses and famine around the world. Climate Change has contributed to the frequency and severity of these issues (Global Climate Change 2020; Draft Climate Science Special Report 2015; Fay 2012; Masson-Delmotte 2018; Letcher 2016).

CHAPTER 3: CARBON DIOXIDE CAPTURE, SEQUESTRATION AND BENEFICIAL REUSE ALGORITHM

This algorithm is being developed to make broad comparisons of carbon dioxide capture and sequestration technologies and reuse options for electrical power plants to explore pathways to maximize carbon dioxide capture and find the most efficient carbon dioxide reuse at the optimal economic benefit. The variables in the algorithm include the type of fuel source for the power plant, the geographical location of the power plant, the most cost effective carbon dioxide capture method and finally the most efficient carbon dioxide reuse available.

Carbon dioxide capture technology dates back to the 1920s. However, carbon dioxide capture was not significantly used until the 1970s in the Texas oil fields when it was used for enhanced oil recovery. Enhanced oil recovery consists of utilizing carbon dioxide to improve the oil and gas production of depleted oil and gas fields. This is accomplished by pressurizing the carbon dioxide into the drilled oil wells, which in turn pressurizes the remaining oil and gas for recovery and production (Carbon Capture Handbook 2015; Elwell 2005; Metz 2005).

There can be significant variations in the cost of carbon dioxide capture technologies. There are multiple variables that contribute to the differences in carbon dioxide capture technology cost. Some of these variables include some of the following: existing (retrofitting) power generation plants, new power generation plants, type of fuel for the power plant, power plant capacity, location of the power plant, type of technology/design used for capture and whether the capture will occur post or pre-combustion. The National Energy Technology Laboratory, part of the U.S. Department of Energy, Office of Fossil Energy developed two reports entitled, Cost and Performance Baseline for Fossil Fuel Energy Plant. The first report was published in 2011: Volume 3b: Low Rank Coal to Electricity: Combustion Cases. This report primarily compares the performance and cost comparison of coal-based power generation plants without and with amine absorber carbon dioxide post-combustion capture technologies. The second report published in 2015, Volume 1a: Bituminous Coal (PC) and Natural Gas Electricity Revision 3, primarily compares the performance and cost comparison of coal-based power generation and natural gas fueled power generation plants without and with an amine based solvent carbon dioxide post-combustion capture technology. I have used the data from the 2015 report to show the comparisons in performance and cost between the coal-fired and natural gas-fired power generation plants, without and with the post-combustion carbon capture technology. I have also adjusted the cost estimates for inflation to 2019 related cost. The first table is the performance comparison and the second table is the cost comparisons (Balat 2007; Cost and Performance 2015; Cost and Performance 2011; U.S. Bureau of Labor Statistics).

Table 2: Performance Summary Comparison for Coal and Natural Gas-Fired Power Plants with and without Amine solvent carbon dioxide post-combustion capture technology (Cost and Performance 2015).

	Pulverized Coal Boiler				Natural Gas Combined Cycle	
Case Name	1[1]	2[1]	3[2]	4[2]	5[3]	6[3]
With CO_2 Capture		Yes		Yes		Yes
PERFORMANCE						
Gross Power Output (MWe)	581	644	580	643	641	601
Auxiliary Power Requirement (MWe)	31	94	30	91	11	42
Coal Flow rate (lb/hr)	412,005	516,170	395,00	495,578	N/A	N/A
Natural Gas Flow rate (lb/hr)	N/A	N/A	N/A	N/A	185,484	185,484
HHV Thermal Input (kWt)	1408630	1764768	1350672	1694366	1223032	1223032
Net Plant HHV Efficiency (%)	39.00%	31.20%	40.70%	32.50%	51.50%	45.70%
Net Plant HHV Heat Rate (Btu/kWh)	8740	10953	8379	10508	6629	7466
Raw Water Withdrawal, GPM	5538	8441	5105	7882	2646	4023
Process Water Discharge, gpm	1137	1920	1059	1813	595	999

Raw Water Consumption, gpm	4401	6521	4045	6069	2051	3024
CO_2 Capture Rate, %	0	90	0	90	0	90
CO_2 Emissions (lb/MMBtu)	204	20	204	20	119	12
CO_2 Emissions (lb/MWh-gross)	1683	190	1618	183	773	82
CO_2 Emissions (lb/MWh-net)	1779	223	1705	214	786	89

[1] Subcritical Pulverized Coal

[2] Supercritical Pulverized Coal

[3] Natural Gas Combined Cycle

Table 2 shows the increased need for power, fuel and water for the amine solvent carbon dioxide capture technology for pulverized coal boilers. The table also shows the loss in efficiencies that accompany the significant reduction in carbon dioxide emission for the pulverized coal boilers. For the Natural Gas Combined Cycle systems, there is more additional power needed for the carbon dioxide capture, but the additional power needed is less than that needed for the coal-fired boilers. The Natural Gas Combined Cycle requires less fuel and the efficiency loss is less than the Pulverized Coal Boilers. The initial carbon dioxide emissions, without carbon dioxide capture technology between the coal-fired power plants and the natural gas-fired power plants in this analysis, is 42% less carbon dioxide emissions for the natural gas-fired power plant for the same power output. The Pulverized Coal Boiler and the Natural Gas-fired power plant with the carbon capture technology both use more water than the plants without carbon dioxide capture, as shown in Table 2. The general conclusion is that the data shows that post-combustion amine solvent carbon capture systems required additional energy, water and resulted in a decrease in net plant efficiencies. However, this carbon dioxide capture technology will significantly reduce the power plants' carbon dioxide emissions. The carbon dioxide capture rates for the amine solvent capture technology are in the range of 90% to 95% (Balat 2007; Cost and Performance 2015; Cost and Performance 2011).

Table 3: Cost Summary Comparison for Coal and Natural Gas-Fired Power Plants with and without Carbon Capture Technology (Cost and Performance 2015).

	Pulverized Coal Boiler								Natural Gas Combined Cycle			
Case Name	1[1]	2019 Cost	2[1]	2019 Cost	3[2]	2019 Cost	4[2]	2019 Cost	5[3]	2019 Cost	6[3]	2019 Cost
With CO_2 Capture			Yes	Yes			Yes	Yes			Yes	Yes
COST												
Total Plant Cost (2011$/kW)	1960	2287	3467	4046	2026	2364	3524	4112	685	799	1481	1728
Total As-Spent Cost (2011$/kW)	2755	3215	4865	5677	2842	3316	4940	5764	901	1051	1945	2270
Cost of Electiricty ($/MWh)(excluding T&S)	82.1	96	133.5	156	82.3	96	133.2	155	57.6	67	83.3	97
Capital Cost	37.8	44	71.1	83	39	46	72.2	84	11.8	14	26.9	31
Fuel Cost	25.7	30	322	376	24.6	29	30.9	36	40.7	47	45.9	54
Cost of Electricity ($MWh)(inlcuding T&S)	82.1	96	143.5	167	82.3	96	142.8	167	57.6	67	87.3	102
CO_2 Transport & Storage (T&S) Cost	0	0	10	12	0	0	9.6	11	0	0	4	5
CO_2 Capture Cost (excluding T&S) $/tonne	N/A	N/A	56.2	66	N/A	N/A	58.2	68	N/A	N/A	71.1	83
CO_2 Avoided Cost (including T&S) $/tonne	N/A	N/A	91	106	N/A	N/A	89.4	104	N/A	N/A	93.8	109
[1] Subcritical Pulverized Coal												
[2] Supercritical Pulverized Coal												
[3] Natural Gas Combined Cycle												
Inflation from 2011 to 2019 - 16.69%												

Table 3 shows the increased cost associate with the implementation of an amine solvent carbon dioxide capture technology. The Total Plant Cost is approximately 43% higher for the coal-fired power plant with a carbon dioxide capture technology option as compared to a similar plant without carbon capture. The Total Plant Cost is approximately 53% higher for the natural gas-fired power plant with a carbon dioxide capture technology option. The capital cost associated with carbon capture from a natural gas plant is approximately half of that from a coal-fired plant. As anticipated all costs for the carbon capture technology options are higher than without the carbon capture option. The data found in the two tables shows the performance comparison and the cost comparison for specific examples with and without an amine solvent post-combustion carbon dioxide capture system. The amine solvent carbon dioxide capture system basically consists of the following equipment: Amine solvent carbon dioxide absorber, low pressure and high pressure pumps, the carbon dioxide dryer and the carbon dioxide compressor. Below are the details and description of the dissertation algorithm (Balat 2007; Cost and Performance 2015; Cost and Performance 2011).

3.1 Algorithm Summary

The first step in this algorithm is to determine whether the power plant in question is a natural gas or coal-fired (fueled) power plant. Natural gas-fired power plants emit 40% to 50% less carbon dioxide than coal-fired power plants. Another variable is if the electrical power plant is existing or a new to be built power plant (Metz 2005; Smith 2013; Wang 2017; Carbon Capture Handbook 2015).

The second step in the algorithm process is to determine the geographical location or region of the world for the power plant's carbon dioxide emissions source. This variable is a critical variable or crucial determination that will affect the cost basis of the capture technology, sequestration method and the carbon dioxide reuse available. A sample question will be where the nearest manufacturer of the specific capture equipment to be used is located in the world.

The third step in this algorithm is to determine the most cost effective carbon dioxide capture technology or technologies that can be implemented for the specific electrical power plant being analyzed. The primary groups of technology include post-combustion, oxy-fuel combustion and pre-combustion capture or carbon dioxide elimination methods. Each group will be discussed later in this section (Carbon Capture Handbook 2015; Metz 2015).

The fourth step in the algorithm is to determine the carbon dioxide reuse options available in the specific region of the world. The question in this step would be, what are the available beneficial reuses of carbon dioxide in the specific region of the world, where the power plant is located or will be built. If there are no viable reuse options, the sequestration methods relevant to that specific region of the world will be determined and included in the costs (Accelerating The Uptake of CCS 2011; Hertzog 2004; Ozin 2018; Perez-Flores 2015; Fay 2012).

The final step in the algorithm is to summarize and finalize the economic evaluation of the most efficient and cost effect sequestration method(s) and the most economical carbon dioxide reuse. This final step is used to maximize carbon dioxide capture and beneficial reuse at the most efficient cost between the three selected control options; thus, minimizing cost to the power producer and eventually to the energy purchasing customer when implementing carbon dioxide capture as an option for reducing the carbon footprint from fossil fuel-fired power plants. This is my primary intention, however, a secondary intention is to make this algorithm replicable into other carbon dioxide emitting industries and sources. This replication should be initiated on a prioritized basis starting with the largest carbon dioxide emitters. This algorithm addresses the largest carbon dioxide emitters, power plants, based on the 2014 IPCC global carbon dioxide emissions inventory (Masson-Delmotte 2018; Pachauri 2015; Rubin 2018; Smith 2013; The Costs of CSS 2015; Wang 2017; Elwell 2005; Gibbins 2008).

Power Plant Carbon Dioxide Capture Algorithm Decisions:

1. Is this an existing or new Electrical Power Plant.
2. Fuel source of the Electrical Power Plant:
    a. Natural Gas-Fired
    b. Coal-Fired (Bituminous, Subbituminous)
3. Geographical Location of the Electrical Power Plant
4. Carbon Dioxide Capture Technology/Technologies to Use

5. Determine beneficial Carbon Dioxide Reuse options
6. An economic evaluation of the Carbon Dioxide Sequestration Technology and Reuse options.

Figure 3.1 presents a carbon dioxide capture technology algorithm decision logic diagram that illustrates the algorithm selections for the type of electric power generation plant, the fuel source for the power, the chosen carbon dioxide capture technology and the carbon dioxide beneficial reuse.

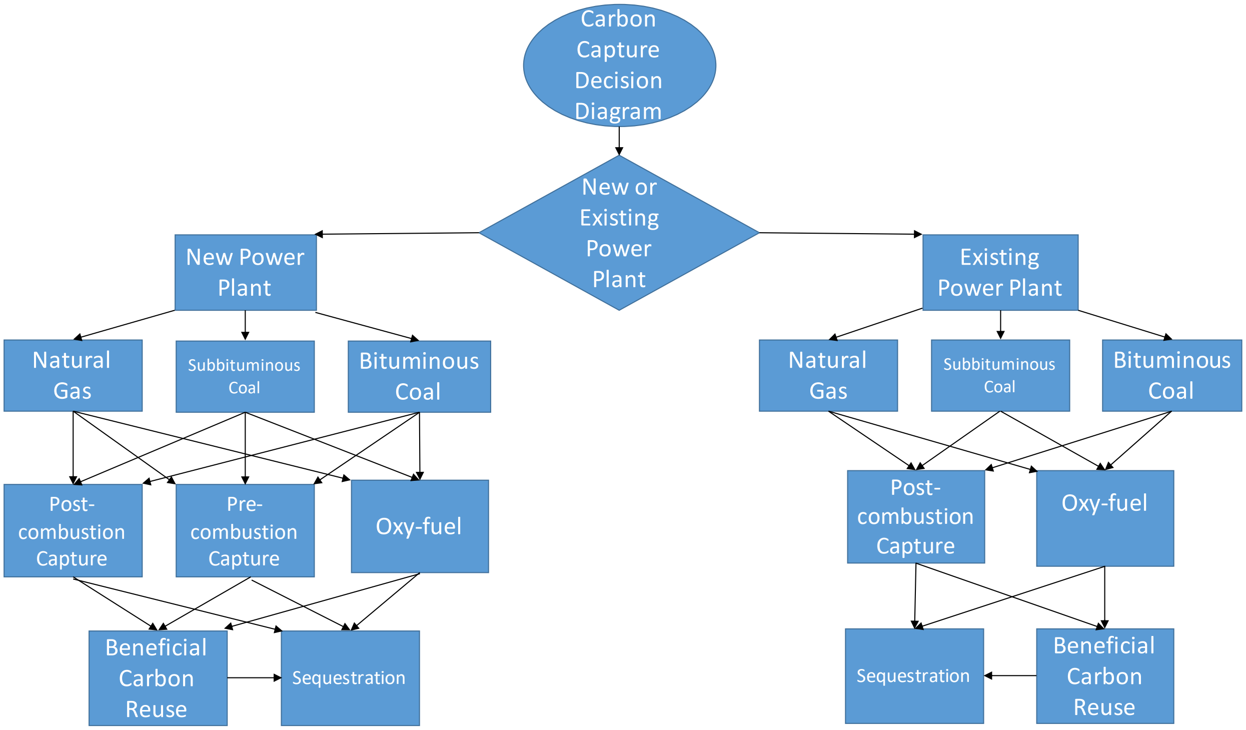


Figure 3.1: Algorithm Decision Logic Diagram (M Garcia 2020)

3.2 Algorithm Equations

The carbon dioxide capture cost equations used in this dissertation are presented below. These equations were used to determine the estimated cost of the carbon dioxide technologies based on the power generation fuel sources. These equations were also used to determine the examples in Chapter 4. These equations include the total cost of the carbon dioxide capture process. This includes the cost of the specific technology, based on the technology cost, the fuel source for the power generation plant and whether the power generation plant is new or existing. Also included, as appropriate are the cost of carbon dioxide transport, sequestration/storage, monitoring and beneficial reuse.

3.2.1 Carbon Dioxide Capture Cost Equations

$$TCCC = CCC + CCT + CCS + CCM + CCAC - CCBR \quad \text{[Equation 1]}$$

TCCC = Total Carbon Dioxide Capture Cost

CCC = Cost of Carbon Dioxide Capture.

CCT = Cost of Carbon Dioxide Transport.

CCS = Cost of Carbon Dioxide Sequestration/Storage.

CCM = Cost of Carbon Dioxide Monitoring.

CCAC = Cost of Carbon Capture Annual Operating Cost.

CCBR = Cost of Carbon Dioxide Beneficial Reuse (Credit). This will often be credit because of the sale of carbon dioxide for beneficial reuse.

There are typically two primary reasons for carbon capture cost estimates and information. These reasons are for technology assessments and for policy assessments. Technology assessments include information for technology selections, capital investments, marketing strategies and for research and development. For policy assessments, the information is used for a number of activities including regulations, legislation, and advocacy (Rubin 2013).

Technology assessment cost estimates, consist of information that is used to compare the cost of different carbon capture technologies. These types of studies focus on the difference in the cost of the different carbon dioxide capture technologies. In these types of analysis, many uniform assumptions are used to keep system parameters the same. Therefore, while these types of technology assessment cost studies can be used as a relative comparison of different options, they are many times not good predictions of the specific project cost. This is because they do not incorporate the many project variations and owner specifications (Rubin 2013).

Policy based assessments are even less rigorous than the technology assessments and are at times a summary of the technology assessment for policymakers. The policy assessments are used as summary information for policymakers to make policy development and regulatory decisions and recommendations on technology implementations, technology research and comparisons, and to advance, in this case, carbon dioxide reduction protocols and commitments locally, regionally and globally. The policy assessments are also used for the advocacy of appropriations toward technology development and research (Rubin 2013).

This dissertation is primarily a technical assessment of the primary carbon capture technologies for coal-fired and natural gas-fired power generation plants. However, there are also aspects of a policy assessment within this dissertation. The policy recommendations are in the final two sections of the dissertation. The technical assessment approach was chosen in order to allow for a more in-depth review of the carbon capture technologies and the challenges associated with the implementation of the technologies.

For specific project cost estimates, the carbon capture technology has already been determined and the purpose of the cost estimate is to accurately reflect all of the project costs for funding purposes. These cost estimates are detailed engineering studies and detailed engineering cost estimates. These detailed engineering studies take many hours of detailed engineering time and hundreds of thousands/millions of dollars and include the design of the carbon dioxide capture process, detailed carbon dioxide capture equipment materials and fabrication cost estimates, process support equipment and utility requirements and cost estimates, engineering services and design costs, direct and indirect labor cost, owner's costs, maintenance cost, annual operating and supplies cost; and project contingencies (Rubin 2013; Balat 2007).

Some of the unique contributing items for specific carbon dioxide capture technology projects include some of the following items: The type of carbon dioxide capture technology to be implemented, power plant size, power plant location, site specifics, power generation technology, power plant fuel characteristics, flue gas process characteristics and carbon dioxide concentration, required and availability of utilities, and final disposition and transport distance of the carbon dioxide. Table 4 contains more details on the specific items that make each carbon dioxide capture project cost unique and the most accurate type of cost estimate (Rubin 2013; Balat 2007).

Table 4: Carbon Dioxide Capture Project Cost Elements

No	**Item**	**Details**
1	Plant Size	Net power output
2	Plant Location	Country, Region of Country, State, etc.
3	Site Characteristics	Plant elevation, atmospheric pressure Design ambient conditions Minimum/maximum design temperatures Design ambient relative humidity Site topography

4	Power generation technology (IGCC, PC, CFB)	Primary technology for converting the fuel into electricity
5	Fuel Type and Characteristics	Coal analysis Natural gas analysis
6	Utilities Availability/Location	Cooling water source and quality Wastewater disposal
7	Flue Gas	Volume Flowrate Composition Carbon dioxide concentration
8	Local cost	Local cost of materials for fabrication Local cost of equipment and materials Local cost of engineering services Local cost of labor Local cost of utilities Local cost of operational supplies
9	Owner’s Cost	Feasibility Cost Surveys Insurance Permitting Financing
10	Carbon dioxide capture equipment	Absorbers, Adsorbers, Gasifiers, Oxy-fuel equipment, etc.
11	Ancillary equipment	Pumps, compressors, heat exchangers, etc.
12	Annual Maintenance	Routine annual maintenance requirements
13	Operational supplies	Solvents, catalysts, chemicals, etc.
14	Sequestration/Storage/Reuse	Type of sequestration/storage or reuse
15	Distance to final disposition	Distance to sequestration/storage, Distance to beneficial reuse

Detailed engineering project cost estimates take many hours to complete and many resources to develop and refine. Although these estimates are the most accurate carbon dioxide capture technology cost estimates, these types of estimates are typically too costly for technology technical comparison and not feasible for this dissertation. Therefore, technology assessment cost estimates will be used in this dissertation for the specific cost example comparisons (Rubin 2013; Balat 2007).

The total Carbon Dioxide Capture Cost equation (Equation 1) consists of six major contributing costs or benefits. These cost equations include the Cost of Carbon Dioxide Capture, which is the cost of the specific carbon capture technology and ancillary equipment required for the carbon capture system. The Cost of Carbon Transport which is the cost of transporting the captured carbon dioxide to a transmission point or possibly to its final usage or sequestration/storage destination. The transport cost consists of constructing a pipeline or shipping the captured carbon dioxide to the nearest existing pipeline (shared pipeline), the shipping connection, or to its final destination depending on the specific circumstance. This would include the labor, materials, installation and operating cost for the new pipeline and required buster pumps or compressors. The transport and usage fees for utilizing existing pipelines would be a potential transport cost. Also, the compression and transportation fees if the carbon dioxide is to be shipped. The cost would be from the point of capture to the final destination of the captured carbon dioxide for beneficial reuse or sequestration. The transport cost would vary from regional to regional depending on the regional cost for labor, materials, construction and transport fees. The Cost of Carbon Dioxide Sequestration/Storage which is the cost to store or contain the captured carbon dioxide. Carbon Dioxide sequestration/storage costs follow closely the cost required for underground injection waste disposal wells. The cost consist of the geological and engineering site location studies, the environmental permitting and regulatory requirements, the construction cost of the underground injections well(s) and the operating/maintenance cost for the sequestration facilities. These are the cost for the owners and operators of the sequestration/storage facilities. There are also the fees and costs assessed to customers for the sequestration/storage of the carbon dioxide in these geological reservoirs or formations. Cost of Carbon Dioxide Monitoring is the cost associated with monitoring the amount of carbon dioxide that is lost during sequestration/storage. Monitoring costs consist of the regulatory required ongoing cost to test and monitor the injection wells and formation integrity. Monitoring costs also include the cost of plugging and post injection site care requirements for the regulatory required time frames, typically 50 years after closure. Sequestration/Storage and monitoring costs will also vary based on the global region, this is based on local labor, material and technical cost. The Cost of Carbon Capture Annual Operating Cost is the cost for the annual utilities, supplies, labor and maintenance for the carbon capture system. The Cost of Carbon Dioxide Beneficial Reuse will often be credit because of the sale of carbon dioxide for beneficial reuse. All of these elements will be reviewed in the paragraphs below (Rubin 2013; Balat 2007; National Energy Technology Laboratory 2017).

$$CCC = [CCT \times PGPC \times IA \times LC] + RFC \quad \text{[Equation 2]}$$

CCC = Cost of Carbon Dioxide Capture
CCT = Cost of Carbon Dioxide Capture Technology (Dollars per kilowatt) ($/kW)
    $CCT_{Post\text{-}Combustion}$ = Cost of Carbon Dioxide Capture Post-Combustion Technology ($/kW)
    $CCT_{Pre\text{-}Combustion}$ = Cost of Carbon Dioxide Capture Pre-Combustion Technology ($/kW)
    $CCT_{Oxy\text{-}Fuel}$ = Cost of Carbon Dioxide Capture Oxy-Fuel Technology ($/kW)
PGPC = Power Generation Plant Capacity (Megawatts)(MW)

IA = Interested Adjustment (Estimate year to 2019)(U.S. Bureau of Labor Statistics)

LC = Location Cost (differences in regional cost of labor, materials, manufacturing, technical support). This is based on the regional cost of labor, the cost of materials and the cost of construction resources. There are a number of International Construction Cost Guides or Indices that can be used to determine the regional construction cost difference, such as the Arcadis International Construction Cost Comparison 2020 (Arcadis 2020).

RFC = Retrofit Cost (additional cost to retrofit carbon capture technology for existing power plants). Retrofit costs include engineering, installation and modification costs to install a unit that was not originally designed for the power plant. Also, additional equipment, replacement equipment and additional utilities required for the carbon capture retrofit.

Other detailed cost factors for carbon dioxide capture cost include the following: power plant location, site characteristics, power generation technology, fuel type and characteristics, utilities available/location, flue gas characteristics, local cost, owner's cost, carbon dioxide capture equipment, ancillary equipment, annual maintenance and operational supplies.

There are a number of avenues to determine the cost of carbon dioxide capture technology. In this section, I will discuss two approaches to determine the cost of carbon dioxide capture technology. The first is the cost method used in Balat 2007. In this technical article, the authors define the carbon capture cost as the difference in the generation cost from a plant with carbon dioxide capture and the generation cost without capture. This is then divided by the difference in the quantity of carbon dioxide produced in the plant with the capture and the emissions from a plant with capture (Balat 2007).

In the equation above I have estimated the cost of the carbon capture technology using the documented cost of carbon capture technologies on a dollars per kilowatt basis and multiplied that by the power generation plant capacity. Then I have used the U.S. Bureau of Labor Statistics interest adjustment to adjust from the estimated cost year to a more recent timeframe. The cost of implementing carbon capture technology will vary by region based on the local cost of labor, technical support, materials and manufacturing. There are global construction guides that can be used to estimate these regional cost differences. If the carbon capture technology will be a retrofit to an existing power generation plant (coal or natural gas) there will likely be additional costs associated with the retrofit. These costs will include engineering, installation and modification cost to install a unit that was not originally designed for the power plant, the electricity output penalty may be higher for a retrofit project, the operating life of the capture unit will be limited to the remaining life of the power plant, and the plant with a retrofit is expected to have a lower efficiency and higher operating cost than a new plant (Balat 2007; Rubin 2013; International Energy Agency 2011; Arcadis 2020).

CCBR = CCBRMV X AACC [Equation 3]

CCBR = Cost of Carbon Dioxide Beneficial Reuse
CCBRMV = Market Value of Carbon Dioxide Captured (Dollars per tonne)
AACC = Annual average carbon dioxide captured (tonnes)

CCT = Cost of Carbon Dioxide Transport. These costs include the following: pipeline construction cost or shipping cost to the nearest existing pipeline (shared pipeline), shipping connection, or final destination cost, the labor, materials, installation and operating cost for the new pipeline and required booster pumps or compressors. The transport and usage fees for utilizing existing pipelines. Also, the compression and transportation fees if the carbon dioxide is to be shipped. The cost would be from the point of capture to the final destination of the captured carbon dioxide for beneficial reuse or sequestration. The transport cost would vary from regional to regional depending on the regional cost for labor, materials, construction and transport fees.

CCS = Cost of Carbon Dioxide Sequestration/Storage. These costs would include the following: The cost of the geological and engineering site location studies, the environmental permitting and regulatory requirements, the construction cost of the underground injections well(s) and the operating/maintenance cost for the sequestration facilities. Also, the fees and cost assessed to customers for the sequestration/storage of the carbon dioxide in these geological reservoirs or formations.

CCM = Cost of Carbon Dioxide Monitoring. These costs include: The regulatory required ongoing cost to test and monitor the injection wells and formation integrity. Monitoring costs also include the cost of plugging and post injection site care requirements for the regulatory required time frames, typically 50 years after closure. Sequestration/Storage and monitoring costs will also vary based on the global region, this is based on local labor, material and technical cost.

CCAC = Cost of Carbon Capture Annual Operating Cost. These costs include: The costs for the annual utilities, supplies, labor and maintenance for the carbon capture system.

3.2.2 Fuel Source Summary

The primary fuel sources for electrical power plants are a critical data point for carbon dioxide capture decisions. This is because there are economic differences when applying carbon dioxide capture to the two primary fuel sources. The two primary sources of fossil fuels for electrical generation power plants are coal and natural gas. Natural gas use as a power generation fuel source generates 40% to 50% less carbon dioxide emissions than the use of coal as the fuel source. However, the cost of carbon dioxide capture on a per ton of CO_2 captured basis for natural gas-fired power plants are typically more expensive than the capture for coal-fired power generation. This will be more apparent in the subsequent cost analysis discussions in this section (Metz 2005; Elwell 2005; Carbon Capture Handbook 2015; International Energy Agency 2006a; Leung 2014; Smith 2013; Wang 2017).

There are two primary types of coal that are predominately used in the electrical power generation sector, Bituminous Coal and Subbituminous Coal. Table 5 below, shows the pounds of carbon dioxide per million British thermal units (Btu) of energy for the listed fuel sources:

Table 5: Pounds of Carbon Dioxide per Million British Thermal Units (Btu) of energy (U.S. Energy Information Administration 2019).

Energy Source	**Pounds CO_2/MMBtu**
Coal Anthracite	228.6

Coal Bituminous	**205.7**
Coal Lignite	215.4
Coal Subbituminous	**214.3**
Natural Gas	**117**

The primary fuels used in this carbon dioxide sequestration algorithm are bituminous coal, subbituminous coal and natural gas. The table indicates that natural gas emits the least amount of carbon dioxide, followed by bituminous coal and then subbituminous coal. Natural gas combustion emits approximately 43% less carbon dioxide than bituminous coal and 45% less carbon dioxide than subbituminous coal. Bituminous coal emits approximately 4% less carbon dioxide than subbituminous coal (Hong 1994; U.S. Energy Information Administration 2019).

3.2.3 Existing or New Electrical Power Plant

Similar to the fuel source question, the existing versus new power generation plant question is also significant. There is a cost difference when a carbon dioxide capture technology is retrofitted into an existing electrical power generation process in comparison to the new design and new installation of the capture technology. Some of the retrofitting costs would include the potential for combustion chamber and burner modifications that may be required for pre-combustion and oxy-fuel carbon capture technology retrofits of existing power generation plants. Also, additional equipment may be required to obtain the required fuel source specifications such as pressure and flow rates (Gibbins 2008; Lueng 2014; International Energy Agency 2006a; Metz 2005).

3.2.4 Location of the Electrical Power Plant

The location of the existing or new power generation plant will affect the cost associated with the carbon dioxide capture technology to be used. Because the majority of petrochemical process design firms are primarily located in the US and Europe, with a few in Japan. The engineering design, fabrication, shipment and installation of the carbon dioxide capture technology will be different for different parts of the world. Other cost variables that are different around the world include the cost of materials and the cost of labor. Also, the carbon dioxide reuse options will affect the overall cost of this algorithm because not all reuse options will be available in all parts of the world (Metz 2005; Accelerating the Uptake 2011; Climate Intervention 2015).

3.3 Summary of Capture Methods/Technologies

There are three primary methods of carbon dioxide capture for electrical power generation plants. These methods include post-combustion methods, pre-combustion methods and oxy-fuel methods. There are a number of experimental carbon capture methods that are currently being researched at this time. However, there is only very limited capture data and economic data for these newer methods (Metz 2005; Carbon Capture Handbook 2015; Global Status of CCS 2017; Herzog 2004; Leung 2014; Wang 2012; Smith 2013; Elwell 2005).

3.3.1 Post-Combustion Carbon Dioxide Capture

The post-combustion carbon dioxide capture methods are technologies that capture the carbon dioxide emissions after the combustion of the fuel sources for electrical generation in this case. Post-combustion carbon dioxide capture technologies are the most researched and most tested methods of the three (3) major technology groups. Post-combustion technologies are also one of the best technologies to use to retrofit an existing power plant that does not have carbon dioxide capture installed (Metz 2005; Carbon Capture Handbook 2015; Elwell 2005; Global Status of CCS 2017; Herzog 2004; Keller 2008; Leung 2014).

The primary post-combustion carbon dioxide capture technology is an amines based solvent absorption technology. For coal-fired power plants, the flue gas emissions are pressurized and forced up a packed chemical absorption column in which an amine is sprayed down on the gas and absorbs the carbon dioxide. There are five (5) different amines that are used in this type of process. However, monoethanolamine (MEA) is the primary amine that has been used and is being used for carbon dioxide absorption. Then the carbon dioxide gas is removed from the amine/carbon dioxide mixture when the gas is removed from the solvent in a steam regeneration unit. The steam/carbon dioxide mixture is condensed separating the water from the carbon dioxide gas. The carbon dioxide gas can then be compressed for transport or sequestration/storage (Metz 2005; Carbon Capture Handbook 2015; Elwell 2005; Global Status of CCS 2017; Herzog 2004; Keller 2008; Leung 2014; Shao 2009).

The primary equipment needed for a post-combustion amines solvent absorption system includes the carbon dioxide removal system (amine solvent absorption column and the carbon dioxide stripper column) and the carbon dioxide compression and drying. Table 6 shows the 2011 and 2019 interest adjusted cost for the post-combustion carbon dioxide capture equipment (Balat 2007; Cost and Performance 2015; Cost and Performance 2011; U.S. Bureau of Labor Statistics).

Table 6: Post-Combustion Equipment Cost Estimate for a 559 MW Output Plant (Cost and Performance 2015)

Description	**2011 Cost Estimate ($/1,000)**	**2011 Cost $/kW**	**2019 Cost Estimate ($/1000) (interest adjusted)**	**2019 Cost $/kW (interest adjusted)**
CO_2 Removal System	$339,591	$608	$396,268	$709
CO_2 Compression & Drying	$38,587	$69	$45,027	$80
Total	$378,178	$677	$441,295	$789

Inflation from 2011 to 2019 16.69%, U.S. Bureau of Labor Statistics

Other amines that are used or are being researched include methyldiethanolamine (MDEA), 2-Amino-2- methylpropanol (AMP), Piperazine (PIPA), diglycolamine (DGA), diethanolamine (DEA), and di-isopropanolamine (DIPA). The amine used depends greatly on the flue gas volume and the concentration of carbon dioxide in the flue gas. There are other post-combustion technologies that are being developed, however, they are not as tested as chemical absorption, they include adsorption, membrane separation, ca-looping and cryogenic fractionation (Metz 2005; Carbon Capture Handbook 2015; Elwell 2005; Global Status of CCS 2017; Herzog 2004; Keller 2008; Leung 2014; Shao 2009).

Another factor to consider is the impact of the higher capital cost, the lower plant efficiency, and the general operating expenses on the cost of electricity. Figure 3.3.1 taken from a recent DOE study shows the increased cost of electricity for two different coal-fired scenarios and a gas-fired system. Note that when transport and sequestration costs are included, the cost of electricity is approximately $61.5/MWh for the coal-fired system and $29.3/MWh for the gas-fired system. Since this study is assuming there may be a potential beneficial use of the carbon dioxide and the algorithm captures the transport costs, it is more appropriate to look at the costs without transport and sequestration, which would be $51.5/MWh for the coal-fired and

$25.3/MWh for the gas-fired systems. It is assumed that these costs will be passed on to the customer through the rate base and therefore are not considered in the subsequent analysis (Cost and Performance 2015).

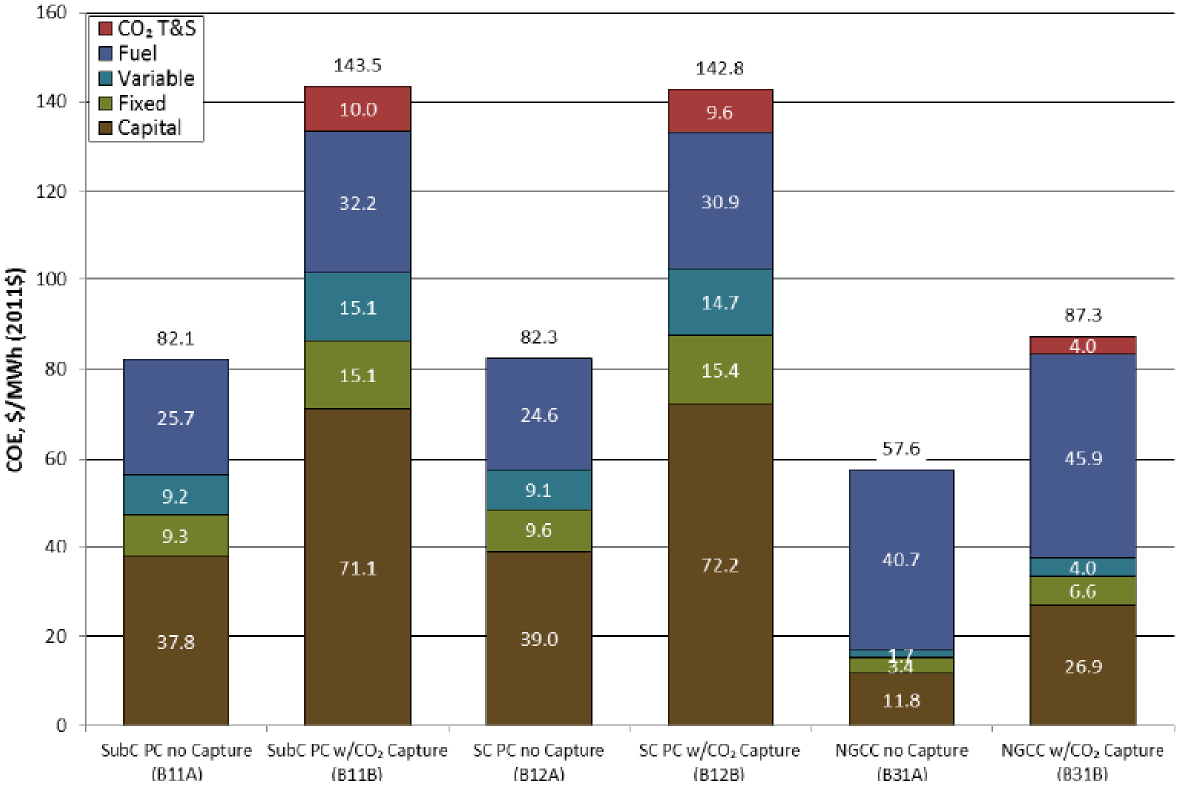


Figure 3.3.1: Comparison of COE for plants with and without CO2 capture (Cost and Performance 2015).

3.3.2 Pre-Combustion Carbon Dioxide Capture

Pre-combustion carbon dioxide capture methods are methods that capture the potential for carbon dioxide emissions before the combustion of the fuel source used for the generation of electricity. The basic premise of pre-combustion carbon dioxide capture is the gasification of coal or steam reforming of natural gas primarily into hydrogen and carbon dioxide. The carbon dioxide can be separated from the hydrogen prior to using the hydrogen for energy production, hence the term, pre-combustion. For coal-fired power plants, pre-combustion most commonly consists of the gasification of the solid coal into a gaseous fuel. This is accomplished by partially oxidizing the fuel source (coal) (Carbon Capture Handbook 2015; Climate Intervention 2015; Gibbins 2008; Global Status of CCS 2017; Herzog 2004; Leung 2014; Metz 2005; Smith 2013; Wang 2017).

There are several methods of gasification technologies that differ in the operational conditions and the method of reaction. For this discussion, I will be summarizing an entrained-flow gasifier. For an entrained-flow gasifier, coal, steam and oxygen are combined in the gasifier and the coal is partially oxidized during the chemical reaction. The resulting fuel is syngas; carbon dioxide, carbon monoxide and hydrogen (Metz 2005; Carbon Capture Handbook 2015; Herzog 2004; Leung 2014; Smith 2013; Wang 2017).

The hydrogen sulfide and carbon dioxide gases are separated out before combustion. There are different methods of carbon dioxide removal including physical absorption or an acid gas removal solvent. This is the most tested and mature technology. Other technologies include membrane removal and hydrogen based separation (Metz 2005; Carbon Capture Handbook 2015; Herzog 2004; Leung 2014; Smith 2013; Wang 2017).

3.3.3 Oxy-Fuel Combustion

The third primary carbon dioxide capture method is oxy-fuel combustion. This method is an intermediate between pre and post-combustion capture. This technology consists of the combustion of the fuel source in a pure or virtually pure oxygen-rich combustion mixture. The oxygen rich and nitrogen free, combustion gas results in emissions that are primarily carbon dioxide and water. The higher concentration of carbon dioxide is easier to separate and purify. The remaining carbon dioxide can be collected and compressed for transport. This technology is still in the development stage for fossil fuel combustion power plant applications (Metz 2005; Carbon Capture Handbook 2015; Herzog 2004; Leung 2014; Smith 2013; Wang 2017).

3.3.4 General Comparison of Control Technologies

Table 7 and Table 8 contain cost ranges for different carbon capture technologies and different fuel sources for new power generation plants. The tables indicate the variability associated with the cost estimates of the different carbon capture technologies and the different power plant fuel sources. Table 7 presents the range of costs based upon the type of system used for generating power and includes transport and sequestration/storage costs while Table 8 presents the range of costs based upon the generic type of control technology (transport and sequestration/storage costs are not included). There is a significant range in the costs from the various authors due to the underlying assumptions made in their studies, the level of detail of their analysis, the time frame of when their study was done, what was included in their analysis (such as if transport, storage, and sequestration are included in the analysis) and other factors. Even though the range of costs are broad, the overall differences between technologies and fuel types are evident, and the total costs associated with carbon capture can be evaluated within a finite range of values.

Table 7: Range of Carbon Capture and Storage Costs for New Power Plants Equipped with Carbon Capture Systems (Akbilgic 2015; Finkenrath 2011; Herzog 2000; Smith 2013)

Item	**PC-CCS**	**IGCC-CCS**	**NGCC-CCS**
Capital Cost, $/kW	1838 – 6560	1815 - 6600	869 - 3750
Cost of Avoided CO2, $/tCO2	34 - 112	20 - 114	45 - 224

- PC = pulverized coal-fired; IGCC = integrated gasification combined cycle; NGCC = natural gas combined cycle; CCS = carbon capture and storage

Table 8: Range of Carbon Capture Technology Costs for New Plants Based upon Carbon Capture Technology (Leung 2014; Finkenrath 2011; International Energy Agency Greenhouse Gas Programme 2005; Hu 2017; Wilberforce 2021; Carapellucci 2019; Psarras 2020)

Fuel Source	**Parameter**	**Post-Combustion**	**Pre-Combustion**	**Oxy-Fuel**
Coal-Fired	Capital Cost, $/kW	1275 – 2096	1820 – 3166	2210 - 2342
	Cost of Avoided CO2, $/tCO2	30 – 41	23 – 43	36 – 37
Gas-Fired	Capital Cost, $/kW	870 – 1556	1180 – 1914	1495 - 1530
	Cost of Avoided CO2, $/tCO2	53 – 58	112 – 187	77 – 102

An important consideration is the additional costs associated with the addition of the carbon capture technology as compared to systems without carbon capture. Not only is the additional capital cost to install the system important, but also the additional electricity cost per kilowatt-hour will be compared. A comparison of the cost of electricity is made in Table 9, with the reported values inflation adjusted for 2019 cost. The cost analysis also compares the cost per kilowatt based on a typical 500 Megawatt power generation plant for post-combustion, pre-combustion and oxy-fuel technologies in Table 9. From these cost analysis comparisons, it is evident which technology could possibly be the most economic to implement for the specific power generation fuel. However, there are different technologies needed in different parts of the world. For example, the US is slowly reducing the number of coal-fire power generation plants and moving to natural gas-fired power generation plants and more renewable energy sources. However, China and India continue to build and commission coal-fired power generation plants because of the abundance and cost effectiveness of the fuel (Metz 2005; Carbon Capture Handbook 2015; Herzog 2004; Leung 2014; Smith 2013; Wang 2017; U.S. Bureau of Labor Statistics).

Table 9: Comparison of the Additional Costs Associated with Various Carbon Capture Technologies (Leung 2014).

Power Plant Fuel Source	Post-Combustion Capital Cost $/kW	Post-Combustion Additional electricity cost cents/kWh	Pre-Combustion Capital Cost $/kW	Pre-Combustions Additional electricity cost cents/kWh	Oxy-Fuel Additional Capital Cost $/kW	Oxy-Fuel Additional electricity cost cents/kWh
Coal-Fired	$723	1.5¢	$520	1.9¢	$1015	3.0¢
Natural Gas	$470	3.5¢	$862	4.4¢	$1307	4.8¢

Table 10: Additional Costs Associated with Installing Carbon Capture Technology on a 500 Megawatt Power Generating Plant (Leung 2014).

500MW Power Generation Plan	Post-Combustion Total Additional CO_2 Capture Cost	Pre-Combustion Total Additional CO_2 Capture Cost	Oxy-Fuel Total Additional CO_2 Capture Cost
Coal-Fired	$361.5M	$260M	$507.5M
Natural Gas-Fired	$235M	$431M	$653.5M

Based on this research and algorithm, the lowest capital intensive carbon dioxide capture technology for an existing coal-fired power generation plant with a gasifier to retrofit would be pre-combustion technology. However, this technology would have a higher additional electricity cost than the post-combustion technology. Based upon the cost of electricity, post-combustion technologies are currently more cost effective due to differences in the operating costs associated with the technology and the impact on the overall plant efficiency. Also, the post-combustion option is only valid as a retrofit for gasification plants. For existing pulverized coal-fired systems and natural gas plants, post-combustion and oxy-fuel are the only viable technologies (Metz 2005; Carbon Capture Handbook 2015; Herzog 2004; Leung 2014; Smith 2013; Wang 2017; U.S. Bureau of Labor Statistics).

The data in Table 10 shows that pre-combustion carbon dioxide capture technology may be the most cost effective for new coal-fired power generation plants. The cost comparison shows that post-combustion carbon dioxide capture technology also has the lowest capital cost for natural gas-fired power generation plants for both new and retrofit options. Based on the research, oxy-fuel technology is the most cost intensive technology of the three detailed in this document. This elevated cost is due to the lack of research, the limited field trials and because this is the most recently developed carbon dioxide capture technology. Oxy-fuel technology also requires additional equipment and additional upgrades of the power plant process, this adds significant cost for the technology. Examples of this additional equipment include the requirement of an air separation unit and a recirculation loop. In reviewing the carbon dioxide capture technologies cost comparisons, pre-combustion is the most cost effective based on estimated capital cost for new coal-fired power generation plants but post-combustion is more cost effective based upon the associated increase in the cost of electricity. Also, post-combustion carbon dioxide capture technology is the most cost effective based on estimated capital cost for natural gas-fired power generation plants (Metz 2005; Carbon Capture Handbook 2015; Herzog 2004; Leung 2014; Smith 2013; Wang 2017; U.S. Bureau of Labor Statistics).

3.4 Beneficial Uses of Capture Carbon Dioxide

There are several possible beneficial reuses of carbon dioxide. Several industries and products use carbon dioxide as a raw material, feedstock or intermediate. Below is a shortlist of potential beneficial uses of carbon dioxide:

1. Methanol production, which is used in the production of paints, plastics, solvents, glues and fuel components.
2. Carbon fiber production.
3. Bioplastics production
4. Carbonated drinks

5. Ethylene glycol production
6. Desalination
7. Drinking water treatment
8. Enhanced oil recovery

(Accelerating the Uptake of CCS 2011; Carbon Capture Handbook 2015; Fay 2012; Metz 2005; Ozin 2018; Perez-Flores 2015).

It is estimated that global anthropogenic carbon dioxide emissions range between 35 and 40 GtCO2. It is also estimated that more than 10 GtCO2 of anthropogenic emissions could be beneficially reused in a number of different industries. However, only a small number of these beneficial reuses actually will sequester the carbon dioxide for any arguable length of time. The majority of beneficial reuses of carbon dioxide will return the carbon dioxide to the atmosphere within a time ranging from days to a few years. Industrial usages of carbon dioxide typically require a purity of 99.5% and food grade carbon dioxide requires purities of 99.9%. The higher purities of carbon dioxide will require additional equipment and will result in increased cost. Table 11 shows the estimated value/potential revenue for a sample of carbon dioxide beneficial reuses. The values range from $30 per ton of CO_2 to $300 per ton of CO_2. However, there are also costs associated with the delivery of the CO_2 to these markets. Table 12 shows the range of cost associated with the transport, sequestration/storage and monitoring of sequestered carbon dioxide (Adlen 2019; Naimes 2016; Letcher 2016; Grant 2017; Rubin 2015; Cost and Performance 2011; Vidas 2009).

Table 11: Examples of the Value of CO_2 for Beneficial Reuse (Adlen 2019; Naims 2016).

Beneficial Reuse	**Value Range $/tCO2**
Enhanced Oil Recovery	40 – 60
Chemical Production	80 – 300
Concrete	30 – 70

Table 12: Cost range for the transport, storage and monitoring of sequestered carbon dioxide (Grant 2017; Rubin 2015; Cost and Performance 2011; Vidas 2009)

Parameter	**Cost Range $/tCO2**
Transport	5.8 – 6.2
Sequestration/Storage	9.71 – 16.22
Monitoring	0.81 - 6.22

Not all of these beneficial reuses are available in all parts of the world. Also, many of these beneficial reuses will not require all of the possible carbon dioxide captured from a power plant. Therefore, there must be a combination of beneficial reuses and geological sequestration/storage. Specific carbon dioxide beneficial reuses will be discussed and evaluated in the example analyses in the following chapters (Accelerating the Uptake of CCS 2011; Carbon Capture Handbook 2015; Fay 2012; Metz 2005; Ozin 2018; Perez-Fortes 2015).

The economic profit from the beneficial reuse of captured carbon dioxide has been difficult to quantify. There is very little public data on the market price for carbon dioxide. However, in 2008, the US Internal Revenue Service (IRS) enacted a carbon oxide sequestration tax credit. The original credit was $10 per ton carbon dioxide captured stored/use for enhanced oil recovery and $20 per ton carbon dioxide captured and store in geological formations. In 2018 the IRS reformed this part of the tax code to allow for $50 per ton of carbon dioxide captured and stored in geological formations and $35 per ton carbon dioxide captured and used for enhanced oil recovery. There are qualifications and timing limits associated with these tax incentives. However, I would recommend that these types of tax credit incentives be expanded and enhanced around the world to promote additional carbon dioxide capture and to encourage and economically bolster carbon dioxide beneficial reuse. These carbon dioxide capture tax credits can be used to offset the cost of the capture technology installations and operating costs. (Beck 2020).

3.5 Carbon Sequestration

Carbon sequestration is the long term storage of carbon dioxide as part of a mitigation strategy to isolate the carbon dioxide from the atmosphere in order to address Climate Change. This section will summarize the primary aspects of carbon dioxide sequestration including geological storage and ocean storage. The intent of carbon sequestration is to ensure the containment or isolation of carbon dioxide for thousands of years (Oelkers 2008; Letcher 2016; Metz 2005).

Geological storage is the sequestration of carbon dioxide in underground depleted oil and gas reservoirs, saline formations, or in un-minable coal beds. After carbon dioxide is captured from its industrial source, it is then compressed and transported to storage/sequestration. The carbon dioxide would be deep well injected into the appropriate geological formation. The site selection would require a geological technical and engineering studies and assessments to determine an appropriate geological formation/location for sequestration. A porous formation without faults and a lower permeable caprock are parameters needed to determine an appropriate geological sequestration location. The carbon dioxide would be injected to depths of more than 800 meters. Environmental assessments and regulatory permitting would also be required for the sequestration operation. Monitoring and integrity testing would be required to ensure the continued long term containment of the carbon dioxide. There are also plugging and post injection care and monitoring requirements (Oelkers 2008; Letcher 2016; Metz 2005).

Ocean storage is a sequestration theory that has been widely researched and assessed. Ocean storage consists of the injection of carbon dioxide deep into the ocean at depths of more than 1000 meters. The carbon dioxide will be isolated from the atmosphere and will dissolve into the ocean. There are environmental concerns for the marine wildlife and higher carbon concentrations within the injection zones. Some other concepts that are being researched that could increase the ocean storage capacity of carbon dioxide include forming carbon dioxide hydrates for deep ocean storage or creating carbon dioxide liquid lakes stored on the ocean floor (Oelkers 2008; Letcher 2016; Metz 2005).

Geological sequestration could contain carbon dioxide for potentially thousands of years. However, ocean sequestration, a potentially viable carbon dioxide containment option, has only been researched and laboratory tested. Pilot testing of ocean sequestration and further field research on the environmental effects still needs to be completed (Oelkers 2008; Letcher 2016; Metz 2005).

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Economics of the Primary Capture, Sequestration/Mitigation Techniques and Technologies

The economic evaluation of this algorithm is possibly the most important section. Capital investments, the cost of carbon dioxide capture, reuse, and sequestration/storage, are possibly the biggest hindrances to the implementation of carbon dioxide capture for the electrical power generation sector and most other sectors that contribute to the global carbon dioxide emissions inventory. Below are the steps of the economic analysis for this algorithm:

1. Capture Technology
2. Fuel
3. Existing/New
4. Location
5. Reuse/Sequestration/Storage
6. Total Economic Evaluation

There is a difference in the capital cost investment for the different types of carbon dioxide capture technologies that will be used. The more mature and tested technologies have been researched to be the least capital intensive and least costly options based on known design needs and scaling needs. However, there is a difference in the capture efficiencies and the reliability of the technologies and this is primarily based on the extent of our lack of research and field testing for the technologies. In the technology summary of the algorithm, the relative implementation cost was discussed and shown. In the following examples, the cost analysis will be reviewed for each of the examples (Carbon Capture Handbook 2015; Elwell 2005; Gibbins

2008; International Energy Agency 2006a; Metz 2005; Rubin 2015; Smith 2013; The Costs of CCS 2015; Wang 2017).

At this point, in general, the cost of carbon capture for natural gas-fired power plants on a dollar per ton CO_2 captured is higher than coal-fired power plants. This is due to a large extent because the carbon dioxide concentration in the coal-fired power plant flue gas is higher than that for gas-fired plants, and therefore relatively less energy is required to separate and concentrate the carbon dioxide. As efficiencies improve this gap in cost could be closed. However, it is important to discuss that natural gas-fired power plants produce 40% to 50% less carbon dioxide than coal powered plants. So this, in enough of itself, is a significant reduction in carbon dioxide. The post-combustion technologies for both fuel sources are well researched and tested, coal-fired more than natural gas carbon dioxide capture (Carbon Capture Handbook 2015; Elwell 2005; Gibbins 2008; International Energy Agency 2006a; Metz 2005; Rubin 2015; Smith 2013; The Costs of CCS 2015; Wang 2017).

Also, part of the economic evaluation is the question of: Is this a new or retrofitted carbon dioxide capture project. Retrofitting carbon dioxide capture technologies cost more than initially designing and implementing the technology (Carbon Capture Handbook 2015; Elwell 2005; Gibbins 2008; International Energy Agency 2006a; Metz 2005; Rubin 2015; Smith 2013; The Costs of CCS 2015; Wang 2017).

The location of the new or to be retrofitted power generation plant will also affect the cost of the carbon dioxide capture technology implementation. The primary petrochemical engineering, designing and construction firms are based out of the US and Europe. There are other firms around the world. So if the engineering firms are in the US or Europe and the existing power plant is in China, there could be an additional cost associated with the engineering, design and construction of the carbon dioxide capture equipment. This could be mitigated by a hybrid approach, such as constructing the carbon capture units in the home country to avoid shipping costs. Also, the use of current meeting and communications technologies (web meetings, conference calls) could assist in lowering this cost of engineering, designing and construction (Carbon Capture Handbook 2015; Elwell 2005; Gibbins 2008; International Energy Agency 2006a; Metz 2005; Rubin 2015; Smith 2013; The Costs of CCS 2015; Wang 2017).

Reuse of the carbon dioxide captured from power generation plants is only part of the solution for carbon dioxide reduction. Most power generation plants will not have the carbon dioxide reuse demand that will require the entire volume of carbon dioxide captured. The best case will be to maximize the beneficial reuse of the carbon dioxide captured given the power generation plants' geographical location. The carbon dioxide beneficial reuses that would utilize the greatest volume of carbon dioxide are enhanced oil field recovery and methane or other fuels from carbon dioxide. However, enhanced oil field recovery will ultimately introduce additional carbon dioxide in the atmosphere, as will many of the carbon dioxide reuse options. There are some beneficial reuses that can capture or convert the carbon dioxide into other compounds. Some examples include the use of carbon dioxide in the production of concrete, the infusion in materials such as plastics and the conversion of other compounds for reuse. Because the carbon dioxide from power generation plants would be steady, this could become the primary feedstock for many chemical plants, chemical plants that produce or use Synthesis Gas (SynGas), methanol, ethylene glycol, carbon fibers, or bioplastics. The power plant carbon dioxide sources would be a steady and reliable feedstock to these types of chemical plants and other industries that utilize carbon dioxide as a feedstock. Some additional beneficial uses of carbon dioxide include carbonated beverages, refrigeration and cooling, fire extinguishing systems and the metal industry (Carbon Capture Handbook 2015; Elwell 2005; Gibbins 2008; International Energy Agency 2006a; Metz 2005; Rubin 2015; Smith 2013; The Costs of CCS 2015; Wang 2017).

The entire economic evaluation will be the evaluation of the topics discussed above: The specific capture technology to be used, the type of fuel for the power plant, whether the power plant is an existing plant or a new plant, the geographical location of the plant and the available carbon dioxide reuse. These variables are the primary factors and combinations that make up the economic evaluation of the carbon dioxide capture technology and beneficial reuse available. The primary intent is to provide pathways that will maximize the carbon dioxide captured and maximize the carbon dioxide beneficial reused, accomplishing these two objectives at the most efficient cost.

The examples below will show the algorithm outcomes and indicate the prioritized implementation based on maximizing carbon dioxide capture at the most efficient cost. The attached Global Power Plant inventory (Appendix B) will also be used to prioritize the implementation.

4.1.1. Electric Power Plant Carbon Dioxide Capture & Reuse Algorithm Examples

1. Natural Gas-Fired Power Plant – Corpus Christi, Texas United States
    a. Natural Gas
    b. Corpus Christi, Texas, Nueces Bay 7
    c. Existing plant post-combustion
    d. Carbon Reuse options in and around Corpus Christi, TX

e. Economic analysis, cost of carbon dioxide capture equipment, delivery, increased cost of electricity, social carbon dioxide cost

For the USA, 33.7% of the electrical power generation plants are fossil fuel-fired power plants. 20% of the power plants are natural gas-fired power plants. Therefore, an existing natural gas-fired power plant has been chosen for this example. The Nueces Bay 7 Natural Gas-fired power plant has an electrical power generation capacity of 633 megawatts. For this power plant, a post-combustion technology unit will be assessed. The cost of this type of unit is approximately \$870 - 1556 per kW. The total carbon dioxide capture capital cost is approximately \$550.7M - \$984.9M. This power plant emits approximately 719,455 t CO_2/yr. The carbon dioxide capture could be as high as 95%. This would be a capture of 683,483 t CO_2 per year and reducing atmospheric emissions to approximately 35,972 t CO_2 per year. According to current studies, the medial global social cost of CO_2 emissions is \$417 per metric ton of CO_2. So for this example, the total social cost of CO_2 emissions avoidance is \$285M per year or about \$13.9B over the average life of a power generation plant (40 years) (Power Plant Nueces Bay 7 2020; Global Power Plant Database 2018; Gibbins 2008; International Energy Agency 2006a; Metz 2005; Rubin 2015; Smith 2013; The Cost of CCS 2015; U.S. Energy Information Administration 2019).

For this Corpus Christi power plant, one possible beneficial reuse of the captured carbon dioxide is the desalination of seawater or brackish groundwater. Corpus Christi recently announced plans to research and build a desalination water plant. There is a new process that has been developed in which carbon dioxide is used to desalinate briny aqueous sources of water into drinking water. With the chemical plants, refineries and power plants in the Corpus Christi area, there is a potential abundance of carbon dioxide and there is a large brackish groundwater aquifer along most of the Texas Gulf Coast. This could be replicated many times along the US coastlines and for many other countries around the world. Other beneficial carbon dioxide reuses in the Corpus Christi area include chemical production, syngas production and plastic manufacturing (Garcia 2012; Novo 2019; Ozin 2018).

In summary, the cost of post-combustion carbon dioxide capture would be approximately $550M – $984.9M capital cost. The increased cost in electricity, which is assumed to be added to the utilities rate base for the sale of electricity, would amount to approximately $106M per year based upon a 65% capacity factor for this 633 MW plant. The annualized carbon capture and cost of electricity would be approximately $120M - $130M for 40 years. Carbon dioxide can be sold in the range of $120 - $350 t CO_2. The beneficial reuse cost range, cost of purifying and transporting the carbon dioxide is between $30 - $300 t CO2. Therefore, the potential economic benefit could be as much as $34.2M - $61.5M per year or $1.4B to $2.5B over the average life of the power plant. The beneficial reuse could reduce the annual cost of carbon capture to approximately $30M - $80M (Gibbins 2008; Leung 2014; International Energy Agency 2006a; Cost and Performance 2015; Arcadis 2020).

2. Coal-Fired Power Plant - Ningbo, China
    a. Coal-Fired
    b. Guodian Beilun Power Station, Ningbo, China
    c. Existing plant Oxy-Fuel
    d. Carbon Reuse options in and around Ningbo China

e. Economic analysis, cost of carbon dioxide capture equipment, delivery, increased cost of electricity, social carbon dioxide cost

For China, 36.9% of the electrical power generation plants are fossil fuel-fired power plants. 5.6% of the power plants in China are natural gas-fired power plants and 31.1% are coal-fired power plants. For this reason, an existing coal-fired power plant has been chosen for this example. The Guodian Beilun Power Station a coal-fired power plant in Ningbo, China has a generation capacity of 5000 megawatts. For this power plant example, an oxy-fuel carbon dioxide capture technology will be assessed. The cost of this type of unit is approximately $2210 - $2342 per kW. The total carbon dioxide capture cost would be approximately $11B - $11.7B. This power plant emits approximately 10.2M t CO_2 per year. The carbon dioxide capture could be as high as 97%. This would be a capture of approximately 9.9M t CO_2 per year and an emissions rate of 306,294 t CO_2 per year. The Guodian Beilun Power Station is comprised of seven (7) different power generation units. So the carbon dioxide capture technology implementation could be staggered over a number of years starting with the highest carbon dioxide emitters. According to current studies, the medial global social cost of CO_2 emissions is $417 per metric ton of CO_2. So for this example, the total social cost of CO_2 emissions avoidance would be approximately $4.1B per year or about $165.2B over the average life of a power generation plant (40 years)(Guodian Beilun 2011; Global Power Plant Database 2018; U.S. Energy Information Administration 2019).

The Guodian Beilun Power Station is near the coastal city of Ningbo, China. There are a number of industries in and around Ningbo, China. There are a number of potential beneficial carbon dioxide reuses in the Ningbo, China region. Because of the many industries in and around Ningbo, carbon dioxide reuse could potentially be significant. There are plastics and chemicals manufacturing, a steel industry, a paper industry and semiconductor industry. All of these manufacturing industries would be able to use carbon dioxide in their processes or as a feedstock (Ningbo China 2017).

There are offshore and onshore oil fields in the Ningbo region of China. The captured carbon dioxide could be used for enhanced oil field recovery. There are also desalination research and testing efforts underway in Ningbo. So the captured carbon dioxide could be used for future desalination opportunities in Ningbo and throughout China (Ningbo China 2017).

In summary, the cost of using oxy-fuel for carbon dioxide capture and beneficial reuse would be approximately \$11B - \$11.7B. However, the Guodian Beilun Power Station is comprised of seven (7) power generation units and the carbon dioxide capture implementation can be phased in a unit at a time or multiple units at a time to absorb the capital cost. The increased cost in electricity, which is assumed to be added to the utilities rate base for the sale of electricity, would amount to approximately \$1.75 billion per year based upon a 65% capacity factor for this 5000 MW plant. Carbon dioxide can be sold for in the range of \$120 - \$350 t CO_2. The beneficial reuse cost range, cost of purifying and transporting the carbon dioxide is between \$30 - \$300 t CO2. Therefore, the potential economic benefit could be as much as \$15.3M - \$891.3M per year or \$19.8B to \$35.7B over the average life of the power plan (40 years). The annualized carbon capture and cost of electricity would be approximately \$2B - \$2.04M. This beneficial reuse could reduce the annual cost of carbon capture to approximately \$1.15B - \$1.98B. Based on the Arcadis International Construction Cost Comparison 2020, the Guodian Beilun Power Station oxy-fuel carbon capture and beneficial reuse would be approximately 25% lower than the Corpus Christi, Texas example. Therefore, the estimated regionally adjusted cost of using oxy-fuel for carbon dioxide capture and beneficial reuse for the project would be in the range of \$8.8B - \$9.4B. This is based on the regional cost of labor, the cost of materials and the cost of construction resources. (Gibbins 2008; Leung 2014; International Energy Agency 2006a; Cost and Performance 2015; Arcadis 2020).

3. Coal-Fired Power Plant – Puducherry, India
    a. Coal-Fired
    b. India
    c. New plant pre-combustion
    d. Carbon Dioxide sequestration near Puducherry, India
    e. Economic analysis, cost of carbon dioxide capture equipment, delivery, increased cost of electricity, social carbon dioxide cost

For this example, a new (non-existing) coal-fired power plant will be reviewed. This new power plant would be located for this review in Puducherry India. This new power plant will be coal-fired and have a capacity of 600 megawatts.

For India, 39.5% of the electrical power generation is from fossil fuels. 7.9% are from natural gas-fired power plants and 29.5% are from coal-fired power plants. Based on this information and information from my research, a new coal-fired power plant has been chosen for this example (Guodian Beilun 2011; Global Power Plant Database 2018).

For this example, a post-combustion carbon capture technology will be assessed. The cost for this type of unit is approximately \$1820 - \$3166 per kW. The total carbon dioxide capture cost would be approximately \$912M - \$1.9B. This power plant emits approximately 1.2M t CO_2 per year. The carbon dioxide capture could be as high as 90%. This would be a capture of 1.1M t CO_2 per year and an emissions rate of 122,517 t CO_2 per year (Guodian Beilun 2011; Global Power Plant Database 2018; U.S. Energy Information Administration 2019).

For this example, the carbon dioxide sequestration cost range will be determined. The sequestration approximate cost will consist of the carbon dioxide transport, sequestration/storage and monitoring cost for the 1.1M t CO2 captured. The approximate annual cost range would be \$17.9M - \$31.6M. This is based on the sequestration cost range in Table 12.

In summary, the cost of pre-combustion carbon dioxide capture would be approximately \$912M - \$1.9B and the annual sequestration cost would be \$17.9M - \$31.5M. Based on the Arcadis International Construction Cost Comparison 2020, the Puducherry India Power Station pre-combustion carbon capture and beneficial reuse would be approximately 50% lower than the Corpus Christi, Texas example. Therefore, the estimated regionally adjusted cost of pre-combustion carbon dioxide capture and beneficial reuse for the project would be in the range of \$456M - \$950M. This is based on the regional cost of labor, the cost of materials and the cost of construction resources The increased cost in electricity, which is assumed to be added to the utilities rate base for the sale of electricity, would amount to approximately \$210 million per year based upon a 65% capacity factor for this 600 MW plant (Gibbins 2008; Leung 2014; International Energy Agency 2006a; Cost and Performance 2015; Arcadis 2020).

For the three regional cost examples in this dissertation, the Arcadis International Construction Cost Comparison 2020 was used to account for regional variability in cost. Based on this international construction cost comparison tool, the Ningbo, China example will be approximately 25% lower cost than the Corpus Christi, Texas example. The Puducherry, India example will be approximately 50% lower cost than the Corpus Christ, Texas example. This is based on the regional differences in the cost of labor, the cost of materials and the cost of construction resources (Arcadis 2020).

4.2 Prioritized Implementation

Carbon dioxide capture is possible for both existing and new electrical power generation plants. Although not inexpensive, the capital cost and operational costs are relatively affordable, and recent tax incentives for carbon capture technology make the cost more competitive. The possible carbon capture options for power generation plants are somewhat limited based on the amount of research and field testing that has occurred for the given technologies. However limited, there are technologies that have been tested and have performed well in the field. Therefore, carbon dioxide capture should be implemented on all coal-fired and natural gas-fired power plants for the top 20 carbon dioxide emitting countries as soon as possible. The priority for carbon dioxide capture should begin with the coal-fired power generation plants because these plants are the most significant carbon dioxide emitters. Then the capture technology should be installed for all natural gas-fired power generation plants. The implementations should begin with China and the United States, followed by India and then Russia as the highest carbon dioxide emitting countries. This should be mandated by the UN. The UN should also mandate the implementation of carbon dioxide capture technology for all new power generation plants around the world, beginning as soon as practical (Carbon Capture Handbook 2015; Elwell 2005; Leung 2014; Metz 2005; The Cost of CCS 2015; Global Greenhouse Gas Emissions Data 2020; Electrical Power Annual 2018).

This implementation could potentially reduce global carbon dioxide emissions by 30% to 33%. The implementation would take four (4) to six (6) years per plant. However, parallel implementations could significantly speed up the installations around the world. The highest capacity fossil fuel-fired power generation plants are in China and Russia. The highest capacity fossil fuel-fired power generation plants are the highest carbon dioxide emitters (Global Greenhouse Gas Emissions Data 2020; Electrical Power Annual 2018).

With carbon dioxide capture technology, carbon dioxide beneficial reuse could also be implemented. The implementation teams would have about two (2) years to determine the carbon dioxide beneficial reuse strategies for each plant and two (2) to four (4) years to implement the strategies. The beneficial carbon dioxide reuse could offset the operational cost of the carbon dioxide capture technology (Accelerating the Uptake of CCS 2011; Fay 2012).

4.3 Climate Change Mitigation and Policies – Summary

Climate Change mitigation strategies and environmental policies are extremely complex topics. This section will summarize the primary mitigation strategies to address Climate Change and the primary Climate Change policies. This discussion will briefly address these complex topics. As stated in other parts of this dissertation, Climate Change is an extremely enormous and exceptionally complex global problem. The Climate Change crisis transcends geopolitical boundaries and affects all parts of the world. Because of the complexity of the Climate Change problem, complex and collaborative mitigation strategies are required to address the challenge (Letcher 2016; Pachauri 2014).

One primary mitigation strategy includes the decarbonization of the global society. Decarbonization would be a sure way to eliminate virtually all of the anthropogenic carbon dioxide emissions. This would be the elimination or substitution of all fossil fuel usage around the world. Even though this would be extremely successful from a Climate Change mitigation strategy standpoint, this would be difficult for the global economies and the advancement of society. Therefore, I think that a gradual, but aggressive decarbonization is warranted. However, I do believe that fossil fuels will continue to be used for many years and specifically in my lifetime, but fossil fuel usage should be significantly reduced, highly regulated and the emissions captured and sequestered. Fossil fuels will continue to be used as a fuel source for many sectors at some limited amounts, however, fossil fuels will need to be significantly and aggressively reduced and replaced with renewable energy sources around the world as soon as possible. This dissertation addresses one portion of the fossil fuel energy sector, power generation.

Global or large scale climate system interventions are known as geoengineering or climate engineering. The two primary geoengineering strategies for Climate Change are solar radiation management and atmospheric carbon dioxide removal. Solar radiation management consists of concepts that will enhance the Earth’s albedo. This is reducing the Earth’s absorption of sunlight, by increasing the amount of sunlight reflected by the atmosphere or the Earth’s surface. All of the primary projects for solar radiation management are in the research or modeling phase at this time. There are a number of potential issues and potential unknown consequences that could be a result of implementing solar radiation management solutions. Some of these proposed ideas include stratospheric cloud enhancement, surface-based reflective enhancements, space-based reflective equipment or particles and upper atmospheric reflective aerosols (Letcher 2016; Sachs 2015; Pachauri 2014).

Atmospheric carbon dioxide removal consists of projects and ideas designed to remove and reduce the amounts of carbon dioxide in the atmosphere. There are several research projects, prototypes and modeled carbon dioxide removal solutions. The potential issues and concerns of these solutions include economies of scale, the global scaling challenges of these projects and the unintended consequences. Some atmospheric carbon dioxide removal ideas include global atmospheric carbon dioxide capture and sequestration, global forest restoration and ocean fertilization (Letcher 2016; Sachs 2015; Pachauri 2014).

Climate Change policy is also a complex topic. These policies are tools and concepts designed to reduce carbon dioxide emitting and change society's usage to renewable energy sources. These concepts penalize, charge, encourage bidding or reward individuals and organizations in order to control, limit and reduce carbon dioxide emissions. There are three primary policy strategies that I will briefly summary. The first policy is carbon taxing. Carbon taxing requires the emitters to pay a tax on every ton of emissions (including carbon dioxide). The primary purpose of a carbon tax is to discourage the use of fossil fuels and encourage the use of renewable energy sources. The next carbon policy is carbon trading. This is when carbon emissions limits are established at reduced levels to meet Climate Change policy obligations. Carbon trading consists of the buying and selling of carbon emissions (in tons) between countries and organizations at these reduced carbon emitting levels. The next carbon policy is carbon dioxide (carbon oxide) tax credits. This is when a government or taxing entity allows tax credits or a tax break to entities that install carbon dioxide capture and sequestration equipment. For example, the US IRS allows a $50 per ton CO_2 tax credit for capture equipment sequestration installed on or after February 9, 2018, and a $35 per ton carbon dioxide tax credit for captured carbon dioxide used for enhanced oil or natural gas recovery (Letcher 2016; Sachs 2015; Pachauri 2014).

Using these and other Climate Change policies, the United Nations has developed Global Climate Agreements aimed at reducing global carbon dioxide emissions. The first Global

Climate Change agreement was the United Nations Framework Convention on Climate Change in 1992, the second Global Climate Change agreement was the Kyoto Protocol in 2007 and the most recent is the 2015 Paris Agreement. These agreements are designed to set global reductions in carbon dioxide emissions and requires countries to submit comprehensive plans to meet these reduced carbon dioxide emissions limits (Edenhofer 2014; Sachs 2015).

As stated before, Climate Change is a large and complex crisis that affects the entire world. As such, successful solutions for Climate Change will require multiple parallel approaches and will require the collaboration and cooperation of multiple professional fields and organizations around the world. This dissertation on electrical power generation carbon dioxide capture, reuse and sequestration is only one solution to one aspect of the many carbon dioxide anthropogenic sources that need to be eliminated or significantly reduced (Edenhofer 2014; Sachs 2015).

A Global Climate Change monetary funding is a concept that I would like to briefly discuss in the last part of this chapter. In 2009 the United Nations began the process to develop a monetary fund to assist the developing nations in their carbon dioxide reduction efforts. However, this process was not formalized and was not completed. I would propose that the UN and the developed nations finalize the details of the monetary fund so that the developing nations can immediately begin using these resources to reduce their carbon dioxide emissions. Table 13 below, is a summary of carbon dioxide mitigation and policy strategies (Edenhofer 2014; Letcher 2016; Sachs 2015; Pachauri 2014).

Table 13: Summary Table for Carbon Dioxide Mitigation and Policy Strategies (Edenhofer 2014, Letcher 2016; Sachs 2015; Pachauri 2014).

Mitigation/ Policy	**Description**	**Advantages/ Disadvantages**	**Relative Cost**	**Time to Deploy**	**Potential Impact**
Decarbonization	Fully decarbonize the global economy	Immediate, significant impact, significant disruption of global economy	High	Long	Significant
Solar Radiation Management	Earth's albedo enhancement	Significant impact, not fully researched, unintended consequences, high cost, scaling issues	High	Long	Significant
Atmospheric CO_2 Removal	Large scale removal of carbon from the atmosphere	Significant impact, not fully researched, unintended consequences, high cost, scaling issues	High	Long	Significant
Carbon Taxing	Taxing tons of carbon emitted	Business incentive for carbon reductions, promotes/funds renewable energy, long time to see effects	Low/ Moderate	Moderate	Moderate
Carbon Trading	Trading reduced tons of carbon allowed to be emitted	Promotes carbon emissions reductions, long time to be effective	Low/ Moderate	Long	Moderate
Tax Credits	Tax credits for tons of carbon sequestered	Business incentive for carbon capture, limitations/restrictions	Low/ Moderate	Moderate	Moderate
Global Climate Agreements	Global agreements to reduce carbon emissions	Significant potential impact, high cost	High	Long	Significant
Global Climate Change Monetary Fund	Monetary fund for developing countries to implement carbon capture	Allows responsible energy development, low to moderate impact	Moderate/ High	Long	Low/ Moderate

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

Global Climate Change is arguably one of the most significant world crises of our time. Global Climate Change is having a detrimental effect on human life, society, the biological systems of Earth and the physical processes of Earth. Global Climate Change is having the most significant effects on the most vulnerable humans on the planet. The poor, the hungry, the old, the very young and the infirmed will be affected most by Global Climate Change. Carbon emissions from fossil fuel-fired power plants are a major contributor to Global Climate Change. Therefore, the primary objective of this dissertation was to develop an algorithm that could be used to evaluate carbon capture technology options that are focused on maximizing carbon dioxide emission capture from the power generation industry while maximizing the beneficial carbon dioxide reuse and sequestration at the optimal cost efficiency. The dissertation addresses how to significantly achieve the IPCC and UN Climate Change goals by potentially reducing global carbon dioxide emissions by approximately 30% to 33% (International Energy Agency 2019; Global Power Plant Database 2018).

In 2018, coal-fired power plants accounted for approximately 30% of the global carbon dioxide emissions, according to the International Energy Agency. If post-combustion carbon dioxide capture technology were to be used to significantly reduce the carbon dioxide from these coal-fired sources, the approximate cost to implement this technology would be in the range of \$2.55T to \$4.19T. If post-combustion carbon dioxide capture technology were to be used to significantly reduce the carbon dioxide emissions for the coal-fired and natural gas-fired power plants of the top three carbon dioxide emitting countries: China, US and India the approximate cost would be in the range of \$2.61T to \$4.3T.

It is critical that actions be taken immediately to curtail and attempt to reverse the detrimental effects of Global Climate Change. This dissertation and the algorithm within this dissertation contain the starting points to initiate the maximum carbon dioxide capture, carbon dioxide beneficial reuse and sequestration at the most efficient cost for the power generation sector. If this dissertation is used to implement carbon dioxide capture, beneficial reuse, and sequestration it would be possible to curtail the current average ambient temperature rise and possibly reverse the Global Climate Change crisis (Masson-Delmotte 2018).

Also, this dissertation and algorithm can be replicated and used to begin reducing or eliminating carbon dioxide emissions within the other sectors currently using fossil fuels that contribute to global carbon dioxide concentrations. Climate Change is an extremely complex global crisis and because of the complexity of the challenges in addressing Climate Change, a multitude of complex responses is required. These complex and multifaceted solutions will require the expertise and collaboration of many scientific and professional experts from around the world. Solving Climate Change will also require the cooperation and involvement of all global nations and international organizations working toward a common goal of carbon dioxide emissions reductions. This dissertation only addresses one complex aspect of Climate Change mitigation, however, it can possibly be replicated to address the capture and sequestration of many other carbon dioxide sources around the globe.

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APPENDIX A: GLOBAL CARBON DIOXIDE INVENTORY

Global Carbon Dioxide Inventory 2014
Thousand Metric Tons of Carbon (CO2 TOT)
From Fossil Fuel Burning, Cement Production and Gas Flaring
Source: https://cdiac.ess-dive.lbl.gov/trends/emis/top2014.tot

				Top 20 Countries	
No.	**Country**	**CO2 TOT**	**Percentage**	**Percentage**	**CO2 TOT**
1	China	2806634	30.19%	81.64%	7589236
2	USA	1432855	15.41%		
3	India	610411	6.57%		
4	Russia	465052	5.00%		
5	Japan	331074	3.56%		
6	Germany	196314	2.11%		
7	Iran	177115	1.91%		
8	Saudi Arabia	163907	1.76%		
9	South Korea	160119	1.72%		
10	Canada	146494	1.58%		
11	Brazil	144480	1.55%		
12	South Africa	133562	1.44%		
13	Mexico	130971	1.41%		
14	Indonesia	126582	1.36%		
15	UK	114486	1.23%		
16	Australia	98517	1.06%		
17	Turkey	94350	1.01%		
18	Italy	87377	0.94%		
19	Thailand	86232	0.93%		
20	France	82704	0.89%		
21	Poland	77922	0.84%		
22	Taiwan	72013	0.77%		
23	Kazakhstan	67716	0.73%		
24	Malaysia	66218	0.71%		
25	Spain	63806	0.69%		
26	Ukraine	61985	0.67%		
27	UAE	57641	0.62%		
28	Argentina	55638	0.60%		
29	Egypt	55057	0.59%		
30	Venezuela	50510	0.54%		
31	Iraq	45935	0.49%		
32	Netherlands	45624	0.49%		

No.	Country	CO2 TOT	Percentage
33	Vietnam	45517	0.49%
34	Pakistan	45350	0.49%
35	Algeria	39651	0.43%
36	Qatar	29412	0.32%
37	Philippines	28812	0.31%
38	Uzbekistan	28692	0.31%
39	Czech Republic	26309	0.28%
40	Nigeria	26256	0.28%
41	Kuwait	26018	0.28%
42	Belgium	25457	0.27%
43	Colombia	22932	0.25%
44	Chile	22515	0.24%
45	Bangladesh	19959	0.21%
46	Romania	19090	0.21%
47	Turkmenistan	18659	0.20%
48	Greece	18358	0.20%
49	Israel	17617	0.19%
50	Belarus	17316	0.19%
51	Peru	16838	0.18%
52	Oman	16681	0.18%
53	Morocco	16325	0.18%
54	Austria	16011	0.17%
55	Libyan Arab	15543	0.17%
56	Singapore	15373	0.17%
57	Norway	12988	0.14%
58	Finland	12899	0.14%
59	Trinidad & Tobago	12619	0.14%
60	Hong Kong	12605	0.14%
61	Portugal	12286	0.13%
62	Ecuador	11977	0.13%
63	Sweden	11841	0.13%
64	Bulgaria	11567	0.12%
65	Hungary	11477	0.12%
66	South Korea	1052	0.01%
67	Serbia	10272	0.11%
68	Azerbaijan	10223	0.11%
69	Switzerland	9628	0.10%
70	Cuba	9500	0.10%
71	Angola	9480	0.10%
72	New Zealand	9453	0.10%
73	Ireland	9290	0.10%
74	Denmark	9135	0.10%

No.	Country	CO2 TOT	Percentage
75	Bahrain	8546	0.09%
76	Syria	8373	0.09%
77	Slovakia	8366	0.09%
78	Tunisia	7862	0.08%
79	Jordan	7213	0.08%
80	Lebanon	6564	0.07%
81	Yemen	6190	0.07%
82	Bosnia	6063	0.07%
83	Myanmar	5899	0.06%
84	Dominican	5874	0.06%
85	Mongolia	5683	0.06%
86	Bolivia	5566	0.06%
87	Estonia	5323	0.06%
88	Sri Lanka	5016	0.05%
89	Guatemala	4998	0.05%
90	Croatia	4593	0.05%
91	Sudan	4190	0.05%
92	Ghana	3945	0.04%
93	Kenya	3896	0.04%
94	Lithuania	3501	0.04%
95	Slovenia	3501	0.04%
96	Zimbabwe	3278	0.04%
97	Ethiopia	3163	0.03%
98	Tanzania	3153	0.03%
99	Cote D Ivoire	3012	0.03%
100	Afghanistan	2675	0.03%
101	Luxembourg	2634	0.03%
102	Kyrgyzstan	2620	0.03%
103	Honduras	2583	0.03%
104	Brunei	2484	0.03%
105	Georgia	2451	0.03%
106	Senegal	2415	0.03%
107	Panama	2400	0.03%
108	Mozambique	2298	0.02%
109	Nepal	2190	0.02%
110	Costa Rica	2116	0.02%
111	Macedonia	2048	0.02%
112	Jamaica	2024	0.02%
113	Botswana	1981	0.02%
114	Cameroon	1910	0.02%
115	Latvia	1902	0.02%
116	Uruguay	1840	0.02%

No.	Country	CO2 TOT	Percentage
117	Cambodia	1823	0.02%
118	Benin	1723	0.02%
119	Papua New Guinea	1723	0.02%
120	EL Salvador	1714	0.02%
121	Cyprus	1653	0.02%
122	Curacao	1604	0.02%
123	Albania	1559	0.02%
124	Paraguay	1555	0.02%
125	Armenia	1508	0.02%
126	Equatorial Guinea	1458	0.02%
127	Uganda	1426	0.02%
128	Gabon	1416	0.02%
129	Tajikistan	1415	0.02%
130	Moldova	1345	0.01%
131	Nicaragua	1326	0.01%
132	Zaire	1274	0.01%
133	Zambia	1228	0.01%
134	New Caledonia	1170	0.01%
135	Mauritius	1153	0.01%
136	Reunion	1138	0.01%
137	Namibia	1024	0.01%
138	Congo	844	0.01%
139	Madagascar	839	0.01%
140	Haiti	780	0.01%
141	Burkina Faso	777	0.01%
142	Palestine	774	0.01%
143	Mauritania	739	0.01%
144	Togo	715	0.01%
145	Guadeloupe	700	0.01%
146	Lesotho	673	0.01%
147	Guinea	668	0.01%
148	Bahamas	659	0.01%
149	Malta	640	0.01%
150	Martinique	627	0.01%
151	Niger	580	0.01%
152	Guyana	548	0.01%
153	Suriname	543	0.01%
154	Iceland	541	0.01%
155	Laos	533	0.01%
156	South Sudan	408	0.004%
157	Mali	385	0.004%
158	Maldives	364	0.004%

No.	Country	CO2 TOT	Percentage
159	Sierra Leone	357	0.004%
160	Macau	350	0.004%
161	Malawi	348	0.004%
162	Barbados	347	0.004%
163	Swaziland	328	0.004%
164	Fiji	319	0.003%
165	Bhutan	273	0.003%
166	Liberia	255	0.003%
167	Aruba	238	0.003%
168	Rwanda	229	0.002%
169	French Polynesia	219	0.002%
170	Saint Martin	200	0.002%
171	French Guiana	200	0.002%
172	Chad	199	0.002%
173	Djibouti	197	0.002%
174	Eritrea	190	0.002%
175	Somalia	166	0.002%
176	Faeroe Islands	163	0.002%
177	Bermuda	157	0.002%
178	Cayman Islands	148	0.002%
179	Antigua & Barbuda	145	0.002%
180	Gibraltar	144	0.002%
181	Gambia	140	0.002%
182	Greenland	138	0.001%
183	Belize	135	0.001%
184	Seychelles	135	0.001%
185	Cape Verde	134	0.001%
186	Timor	128	0.001%
187	Andorra	126	0.001%
188	Burundi	120	0.001%
189	Saint Lucia	111	0.001%
190	Bonaire	88	0.001%
191	Central African Rep	82	0.001%
192	Guinea Bissau	74	0.001%
193	Palau	71	0.001%
194	Grenada	66	0.001%
195	St Kitts	63	0.001%
196	Turks Caicos	56	0.001%
197	Solomon Islands	55	0.001%
198	Samoa	54	0.001%
199	British Virgin islands	49	0.001%
200	Comoros	42	0.000%

No.	**Country**	**CO2 TOT**	**Percentage**
201	Vanuatu	42	0.000%
202	Micronesia	41	0.000%
203	Anguilla	39	0.000%
204	Dominican	37	0.000%
205	Tonga	33	0.000%
206	Sao Tome	31	0.000%
207	Marshall Islands	28	0.000%
208	St Pierre & Miquelon	21	0.000%
209	Cook Islands	19	0.000%
210	Kiribati	17	0.000%
211	Falkland Islands	15	0.000%
212	Montserrat	13	0.000%
213	Nauru	13	0.000%
214	Liechtenstein	12	0.000%
215	Wallis & Futuna Islands	6	0.000%
216	Saint Helena	3	0.000%
217	NIUE	3	0.000%
218	Tuvalu	3	0.000%
	Total	**9295610**	

APPENDIX B: GLOBAL ELECTRICAL POWER PLANT INVENTORY

Here are the top 50 Coal-Fired Power Generation Plants based on electrical generation.

2018 Global Power Plant Database
World Resources Institute

Countr	Country_lo	Name	gppd_idnr	capacity_mv	latitud	longitu	primary_fue
CHN	China	East Hope Metals Wucaiwan power station	WRI1075600	7000	44.6885	89.1138	Coal
CHN	China	Datang Tuoketuo power station	WRI1070659	6720	40.1947	111.3589	Coal
TWN	Taiwan	Taizhong Taichung	WRI1000364	5500	24.2131	120.485	Coal
POL	Poland	BeÅ‚chatÃ³w	WRI1023817	5472	51.2679	19.3265	Coal
IDN	Indonesia	PLTU Paiton I Unit 7 & 8	WRI1000941	5355	-7.7184	113.5827	Coal
CHN	China	Waigaoqiao power station	WRI1070165	5240	31.3536	121.6003	Coal
KOR	South Korea	Yeongheung	WRI1000187	5080	37.2369	126.4361	Coal
CHN	China	Guodian Beilun power station	WRI1070245	5060	29.9433	121.8131	Coal
CHN	China	Guohua Taishan power station	WRI1070085	5000	21.8664	112.9228	Coal
CHN	China	Jiaxing power station	WRI1070511	5000	30.6283	121.1436	Coal
IND	India	VINDH_CHAL STPS	IND0000503	4760	24.0983	82.6719	Coal
IND	India	MUNDRA TPP	IND0000278	4620	22.823	69.5532	Coal
CHN	China	CPI Pingwei power station	WRI1070763	4540	32.6842	116.9021	Coal
CHN	China	Zouxian power station	WRI1072548	4540	35.3256	116.9261	Coal
CHN	China	Datong - Tashan Coal	WRI1070203	4520	39.9261	113.0843	Coal
CHN	China	Huaneng Qinbei power station	WRI1070183	4400	35.1679	112.7162	Coal
CHN	China	Ninghai power station	WRI1070515	4400	29.481	121.5109	Coal
CHN	China	Houshi power station	WRI1070440	4200	24.3031	118.1261	Coal
CHN	China	Huaneng Yuhuan power station	WRI1070649	4200	28.1142	121.1398	Coal
TWN	Taiwan	Mailao	WRI1000362	4200	23.8033	120.1902	Coal
MYS	Malaysia	Manjung power station	WRI1000255	4180	4.1586	100.6423	Coal
CHN	China	Huaneng Haimen power station	WRI1070797	4144	23.1899	116.6553	Coal
ZAF	South Africa	Kendal power station	WRI1000125	4116	-26.088	28.9689	Coal
ZAF	South Africa	Majuba power station	WRI1000129	4110	-27.0955	29.7706	Coal
CHN	China	Castle Peak power station	WRI1070187	4108	22.376	113.9214	Coal
JPN	Japan	Hekinan power station	WRI1000637	4100	34.8352	136.9609	Coal
USA	United States	W A Parish	USA0003470	4008.4	29.4828	-95.6311	Coal
CHN	China	Guodian Taizhou power station	WRI1070626	4000	32.1872	119.9145	Coal
IND	India	MUNDRA UMPP	IND0000279	4000	22.8158	69.5281	Coal
KAZ	Kazakhstan	Ekibastuz-1 power station	WRI1000286	4000	51.888	75.377	Coal
KOR	South Korea	Boryeong (poryang)	WRI1000191	4000	36.402	126.49	Coal
KOR	South Korea	Dangjin	WRI1000208	4000	37.0543	126.5133	Coal
KOR	South Korea	Hadong	WRI1000202	4000	34.9512	127.8213	Coal
KOR	South Korea	Taean	WRI1000196	4000	36.904	126.233	Coal
CHN	China	Datong power station	WRI1070449	3990	40.0279	113.2933	Coal
ZAF	South Africa	Matimba power station	WRI1000130	3990	-23.6678	27.6128	Coal
CHN	China	Guangdong Shajiao power complex	WRI1070089	3970	22.7489	113.6807	Coal
CHN	China	Ligang power station	WRI1070158	3960	31.9403	120.0764	Coal
CHN	China	Xinyuan Aluminum power station	WRI1070716	3960	36.6148	116.2194	Coal
IND	India	SASAN UMPP	IND0000395	3960	23.9784	82.6275	Coal
CHN	China	Shidongkou power station	WRI1070164	3820	31.4651	121.4048	Coal
RUS	Russia	Reftinskaya GRES	WRI1003790	3800	57.1067	61.7117	Coal
CHN	China	Suizhong power station	WRI1070527	3760	40.0793	120.0089	Coal
CHN	China	Huaneng Shangdu power station	WRI1070661	3720	42.2237	116.0293	Coal
ZAF	South Africa	Lethabo power station	WRI1000128	3708	-26.7403	27.975	Coal
ZAF	South Africa	Tutuka power station	WRI1000135	3654	-26.7767	29.3527	Coal
CHN	China	Wujiaqu power station	WRI1070286	3640	44.2686	87.6881	Coal
ZAF	South Africa	Duvha power station	WRI1000119	3600	-25.9595	29.3409	Coal
ZAF	South Africa	Matla power station	WRI1000131	3600	-26.2804	29.1423	Coal
UKR	Ukraine	Vuglegirska power station	WRI1005107	3600	48.4652	38.2027	Coal

ABOUT THE AUTHOR

Michael D. Garcia, P.E., CSP is currently the Executive Director, Regulatory Affairs for the Austin Community College in Austin, Texas. Michael has district wide responsibilities for the environmental, health and safety programs, policies and management systems for the College. He is also responsible for risk management, emergency response and emergency management systems and emergency planning for the district. The Austin Community College (ACC) consists of eleven (11) campuses, encompasses more than 70,000 total students and more than 42,000 full-time students. ACC also has more than 8,000 faculty and staff for a district that encompasses four (4) Central Texas counties.

Michael has been in the environmental engineering field for more than twenty-five (25) years. He received his Bachelor of Science from Texas A&M University - College Station, Texas in Civil and Environmental Engineering in 1995. Michael completed a Master of Science in Environmental Engineering (Environmental Planning and Management) from the Johns Hopkins University Whiting School of Engineering in 2014. He is currently a doctoral candidate in Environmental Engineering at the University of North Dakota College of Engineering and Mines. Michael's research interest is in Climate Change and Sustainability. Specifically Climate Change mitigation, adaptation, sequestration, Sustainable manufacturing and Sustainable development.

Michael's career began at Hoechst Celanese specialty chemicals at the Bay City, Texas chemical plant as an Environmental Engineer. He was also a Corporate Environmental Engineer for the HEB Food Manufacturing and Food Distribution Company in San Antonio, Texas. Michael also worked for the 3M Company in Austin, Texas. Throughout his career, Michael has coordinated and managed many aspects of corporate environmental, health, safety, sustainability and emergency management programs and management systems.