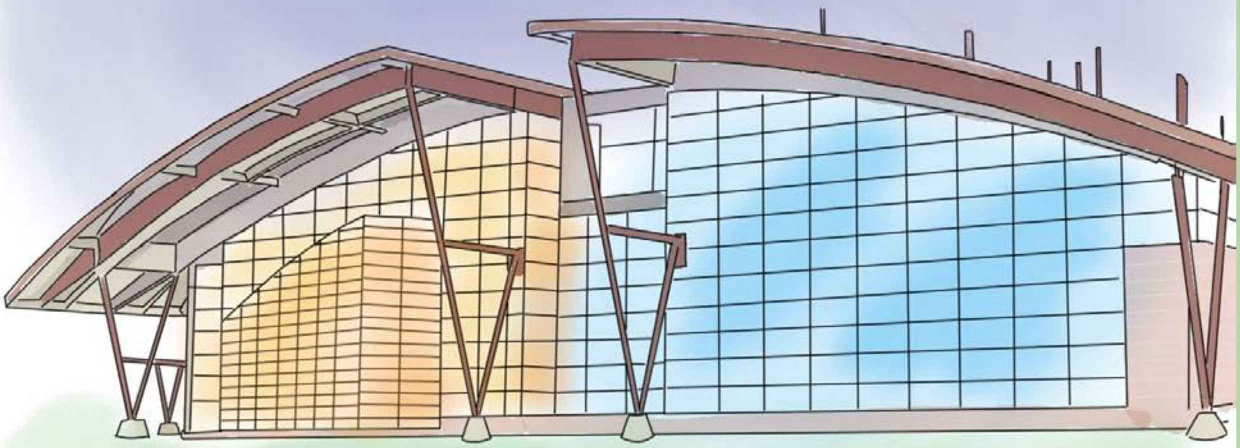
Making Fossil Fuel Plants Go Green

How UMass Amherst Can Reach Carbon Neutrality



The Carbon Capture Team

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Executive Summary

The Central Heating Plant at the University of Massachusetts Amherst served as a milestone for the campus: the transition from the use of coal to natural gas to heat and power university buildings. However, it has become increasingly evident that more needs to be done to mitigate UMass's carbon emissions. The goal to become a carbon neutral campus by the year 2030 has been set by the university chancellor as well as the Carbon Mitigation Task Force. There are several proposed methods to achieve this goal, such as expanding UMass's renewable energy portfolio and redesigning buildings to make them more environmentally friendly. Although these ideas to reach net-zero carbon emissions would help bring UMass closer to net-zero, they are not sufficient alone to realistically attain this goal. Carbon capture and storage, a promising technology that has garnered much attention over the last two decades, would be able to mitigate the majority of campus emissions—and may present the only feasible method to reach our goal by 2030.

Chapter 1: Introduction to CCS

Like the rest of the world, UMass Amherst faces a complicated challenge: how to reduce its greenhouse gas emissions. The ideal solution would be through the use of renewable energy. However, as we show in Chapter 2, the low efficiencies of current renewable energy technologies and the non-optimal location of the UMass campus make it unlikely that renewables alone can allow UMass to reach carbon neutrality. While renewable energy technologies continue to improve, UMass needs a way to reduce its carbon emissions in the meantime; carbon capture and storage technology shows potential to be this critical stepping stone in carbon mitigation efforts.

Carbon capture and storage (CCS) technology was introduced with the purpose to aid enhanced oil recovery (EOR) in the 1970’s, in which carbon is injected deep into underground oil wells to recover the oil that exists within these geological formations [1]. CCS was reintroduced with the purpose of sequestering carbon emissions that would otherwise leak into the atmosphere in the 2000’s [2]. CCS technology has proved successful in dozens of projects globally, including near the UMass campus. The largest CCS site that is currently in operation is the Century Plant in Pecos County, Texas, which captures 8.4 million tons of CO2 per year, which is then used for EOR projects [3].

UMass Amherst is among the largest universities in the state, and consumes significant amounts of energy daily. All of the campus’s heat and most of its electricity is generated by the award-winning Central Heating Plant (CHP), a natural gas-fired cogeneration plant. Although the CHP releases carbon emissions into the air, it is considered extremely efficient and it is still relatively young. CCS would allow UMass to keep the CHP running while eliminating nearly all of its harmful carbon emissions. Furthermore, several potential sequestration sites near Amherst, Massachusetts make implementation of CCS at the CHP a viable option.

Although CCS is a fairly new technology, it has demonstrated great potential in mitigating carbon emissions at both small-scale operations and large, commercial ones. It may not be the final solution to achieving a carbon-neutral campus, but it is a necessary step that UMass must take in order to mitigate its CO2 emissions by the year 2030.

Chapter 2: The Problem at UMass Amherst

The University of Massachusetts Amherst contributes to about 14% of the overall carbon emissions of all state agencies in Massachusetts, making the campus the top emitter in the state [4]. This is not to say that UMass has done little to achieve sustainability; aside from its campus-wide composting initiative and its 15,000 solar panels, the university replaced its eighty-year-old coal-fired power plant with the new Central Heating Plant (CHP) that relies on natural gas to reduce greenhouse gas emissions by 27% in 2009. This project cost the university $133 million, and the CHP itself has won several awards for its efficiency in combining a combustion turbine with a steam turbine, as well as implementing a solar water heater to further reduce carbon emissions [5]. Despite the efficiency of the CHP, UMass Amherst is the home to thousands of students and faculty, and the population is expected to grow with the expansion of campus. A substantial increase in the campus's energy demand and therefore carbon emissions will be faced in the coming years. Although renewable energy sources are ideal, the efficiency of such technology is not feasible to cut campus emissions to net zero by 2030, and carbon capture and storage is essential in UMass Amherst's goal to reach a carbon neutral campus.

Solar and Wind are not Enough

At the forefront of renewable energy, solar technology was implemented on the UMass campus in 2017. The 15,576 first-generation silicon solar panels are seen atop the Fine Arts Center, on the Recreation Center, and in various campus parking lots; yet they account for less than 4% of the annual energy demands of campus [6]. This is largely due to the fact that the highest efficiency solar panels on the market are only 22.8% efficient [7]. Furthermore, many factors affect the efficiency of solar photovoltaic cells, making them costly and unreliable over time. For example, an extreme increase in temperature has the potential to damage the photovoltaics and decrease the cells' efficiency [8]. In New England, these significant temperature differences are inevitable. The possibility of wind power has also made an appearance at UMass; however, the wind speeds in Western Massachusetts do not reach the necessary wind speeds of about 14.3 mph at 50 meters above ground for optimal energy production from a wind turbine [9, 10]. CCS does not face these meteorological or geological shortcomings. CCS is a technology that can eliminate at least 90% of carbon emissions from the CHP. Additionally, CCS can be retrofitted to the university's CHP, making it an attainable, cost-efficient method of reducing carbon emissions [11].

Our Geographic Location Limits Geothermal Potential

Besides these weather-dependent renewable energy sources, geothermal energy is another technology that UMass has looked into. By using earth's thermal energy to generate hot and cool steams, Ball State University is a successful example of the largest geothermal power plant. With the plant built in 2012, it was able to cut its carbon emissions by nearly half [12]. However, whether it will be fitted and a viable option for UMass is another question. Since UMass is twice the size of Ball State in size, the cost to build a new power plant to replace the award-winning CHP would be twice the cost of Ball State's system, approximately $150-200 million [12]. This is far more expensive than the CHP. Moreover, Massachusetts does not have tremendous geothermal potential. In a geological survey conducted by UMass Amherst, the temperature three kilometers beneath the surface of the Amherst region is only in the range of 50-75 degrees Celsius, which is lower than average boiling steam, 100 degrees Celsius [13]. Three kilometers is twenty-five times deeper than the depth of Ball State's thermal wells. The cost to install such a large geothermal system and the location of UMass Amherst deems the implementation of a geothermal system on campus unfeasible.

Carbon Capture is the Way to Net Zero

Another option for achieving net zero is relying on natural carbon sinks across UMass Amherst's 587 hectares. However, even if this amount of land could sequester carbon at the ideal rate of a temperate forest (~60 tonnes/hectare) [14, 15], it would still not be able to offset the amount of carbon released by the CHP (~110,000 MtCO2/year, as shown in part 1 of the Appendix) [16]. It is evident that the implementation of carbon capture technology is necessary to reduce our carbon emissions to net zero. While UMass Amherst should take the steps to expand its renewable energy portfolio, the technological inefficiencies and geological location of campus hinder the potential of renewable energy to meet the university's electricity needs, and therefore cannot stand alone in reaching carbon neutrality by 2030. Carbon capture technology, on the other hand, has the ability to capture 90% of emissions from the CHP, which accounts for the majority of campus emissions. After accounting for other sources of CO2 as well as the energy penalty associated with CCS, implementation of CCS at UMass was calculated to be able to mitigate nearly 80% of total campus emissions (Appendix, part 4). Thus, CCS would allow the University of Massachusetts to erase its carbon footprint in a cost- and energy-efficient way.

Chapter 3: The Technology Behind CCS

CCS has been highlighted repeatedly by organizations such as the International Panel for Climate Change (IPCC) as a key way to reduce greenhouse gas emissions and mitigate the effects of climate change [17]. CCS consists of three steps: capturing CO_2 directly at the source, compressing the CO_2 for transportation, and sequestering the CO_2 permanently. Although there are several possible methods of carbon capture, post-combustion capture is the most mature of these technologies and allows for retrofitting of existing plants [18]. By implementing post-combustion CCS at the Central Heating Plant, the campus's overall emissions can be cut drastically.

The Post-Combustion Capture Process and How It Works

The post-combustion process involves separating CO_2 from other flue gases, mainly N_2, after fossil fuel combustion [19]. Currently, amine-based solvents are the most developed technology to accomplish this [20]. An amine-based solvent refers to an aqueous solution of an alkanolamine [21]. There are a variety of different amine solvents that can be used, including diethanolamine (DEA), monoethanolamine (MEA), and 2-amino-2-methyl-1-propanol (AMP) [22]. The main advantages of using amines as chemical absorbents are their high chemical reactivity with acid gases like CO_2, high CO_2-loading capacity, and low cost to produce [20].

The most widely used amine solvent by far is MEA. Due to being a primary amine, it is very reactive and can capture 85% to 90% of the CO_2 from flue gas, despite the low CO_2 concentrations present. It also has a fast reaction rate, making it an overall very effective solvent [23]. As seen in Figure 1, one mole of CO_2 reacts with 2 moles of MEA. The reaction highly favors the formation of products at cool temperatures, while the reactants are favored at high temperatures [21].

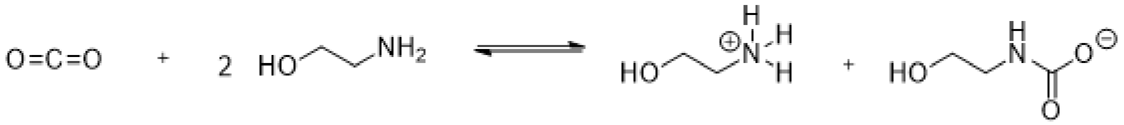

Figure 1. Main reaction of CO_2 with MEA [21].

An aqueous solution of about 30% MEA by weight is needed for the post-combustion capture process [24]. This process is illustrated in Figure 2. First, the solvent reacts with and binds the rising CO_2 in the absorber column, separating it from the other gases to produce a CO_2-rich amine solution [20]. This solution is then transferred to the stripper column, where it is heated between 115-123 °C to reverse the reaction [21]. This regenerates the solvent for reuse and leaves behind a relatively pure stream of CO_2 that can be compressed and sequestered [20].

The main issue with the MEA-based capture process is the high energy penalty incurred by the solvent regeneration step, which can decrease the overall efficiency of a power plant by 15 to 30% [25]. Therefore, alternative options to MEA should also be considered.

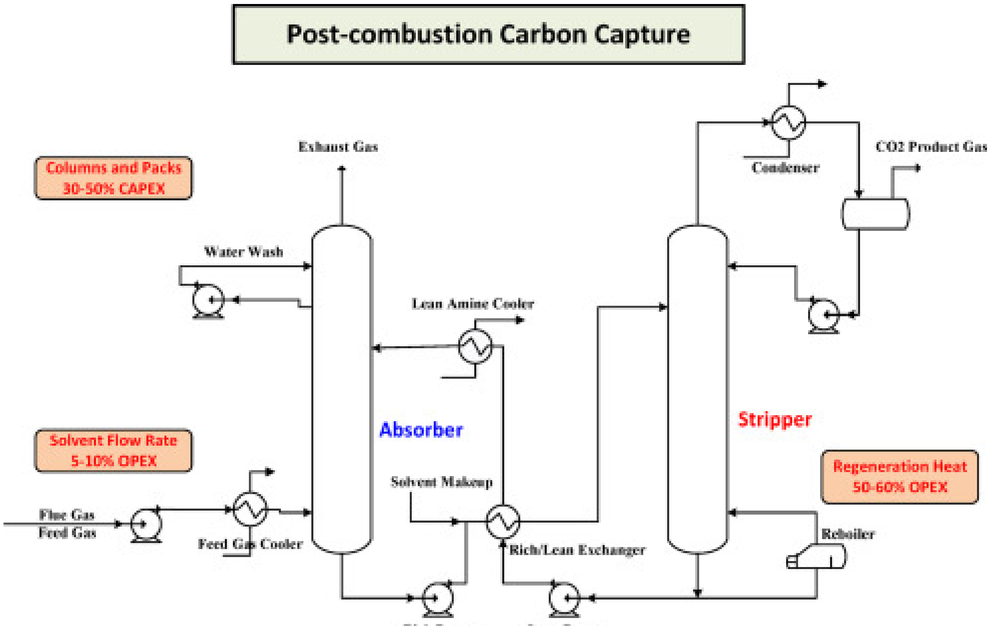

Figure 2. Diagram of the post-combustion carbon capture process using solvent absorption [20].

The second generation of carbon capture that shows great potential for replacing amine solvents is calcium looping (CaL). Calcium looping uses the reversible reaction between CaO and CO_2 to capture CO_2 in one reactor (the carbonator) and then reverse the reaction in another reactor (the calciner), leaving behind nearly pure CO_2. Due to modern steam cycles already operating at close to the temperature needed to reverse the reaction, there is no extra energy penalty to pay for solvent regeneration [26]. One study showed that CaL had a 98% carbon capture rate while decreasing electric costs by 14% compared to traditional amine solvents [27]. The main drawback of this technology, however, is that it is still being researched, and is not yet available for large-scale use.

The Methods of Carbon Sequestration

Once the CO_2 has been captured, it can be sequestered in two ways: injection in deep geological formations or mineral carbonation. Such geologic formations include depleted oil and gas fields, deep saline aquifers, and basalt rock formations [28]. The most common form of CO2 sequestration is in oil and gas reservoirs for enhanced oil recovery projects; depending on the location of the power plant, however, saline aquifers and basalt storage can provide more feasible options for geological sequestration.

Saline aquifers are porous rock formations such as sandstone that contain high-salinity water in the pores known as brine. The CO_2 is injected into the pores about 500-3000 meters below the surface, where the pressure is high enough that the CO_2 maintains its dense supercritical liquid form for storage. Some CO_2 will react with the brine in the pores, while the rest of the CO_2 will remain within the pores of the saline aquifer [29]. Above deep saline aquifers must exist impermeable layers of rock that keep the CO_2 from escaping [28]. Carbon sequestration in deep saline aquifers does not pose many environmental risks, nor would this method affect freshwater supply.

Another method of geological carbon sequestration is through deep basalt storage. Because basalt rocks are rich in calcium, iron, and magnesium, the injected carbon can be stored permanently by reacting to form solid carbonate minerals [30]. Although basalt storage is still a budding technology and has not yet been implemented at any CCS sites, its potential should be looked into further.

Unlike geologic sequestration, in which carbon must be transported to a pre-existing geological formation, mineral carbonation can be used to sequester carbon *in situ.* Mineral carbonation is the fixation of CO_2 into highly stable carbonate minerals [31]. It is advantageous in that the reactions involved require no energy inputs: in fact, they release heat, as seen in Figure 2. This is due to carbonates having a lower energy state than CO_2 [32].

$$\mathrm{CaO} + \mathrm{CO_2} = \mathrm{CaCO_3} + 179\ \mathrm{kJ/mole}$$

$$\mathrm{MgO} + \mathrm{CO_2} = \mathrm{MgCO_3} + 118\ \mathrm{kJ/mole}$$

Figure 2. Carbonation reactions of binary oxides MgO and CaO [32].

The main challenge with mineral sequestration is that despite being highly favored thermodynamically, the carbonation reactions are very slow (up to 100,000 years). Various reaction pathways are currently being studied to speed up the carbonation reaction. One method is to first dissolve the minerals in a solution so that they can more readily react with CO_2. The best way to achieve this while minimizing the energy penalty as much as possible would be to dissolve the serpentine in molten $MgCl_2$ salts, which could then be recycled. However, this process is considered corrosive. To mitigate the potential negative environmental impacts of this process, research has been done to dissolve the minerals in water with pre-treatment, but this reaction is energy intensive [32]. So far, although there have been many efforts to reduce the reaction time of mineral carbonation, there is still no commercially viable process to date.

The CHP accounts for the majority of the electricity, heating, and cooling demand by the UMass Amherst campus. In order to attain the goal of reaching a carbon-neutral campus by 2030, it is necessary to tackle the CHP's carbon emissions by installing CCS. Although post-combustion technology is the best fit for the CHP, there are still many decisions that remain concerning its implementation, ranging from how to best trap the CO_2 to how to store the carbon.

Before implementing CCS at the CHP, cost-effectiveness, energy efficiency, and local geologic characteristics must all be considered.

Chapter 4: Implementation at UMass Amherst

Although CCS is still a budding solution to tackling climate change, it shows great promise. Already, there are 22 carbon capture projects around the world: 16 of these are in the United States. However, only three of these CCS projects are for power generation [33]. As such, the CHP at UMass Amherst presents an incredible opportunity for the implementation of carbon capture at a power plant. Not only would implementing CCS at the CHP eliminate the campus's largest source of carbon emissions, but it would also lead the way for wider use of the technology, particularly by other colleges and universities. In order to implement CCS, however, many costs must be considered, from capturing the CO_2 from the flue gas, compressing it to a supercritical fluid, transporting it to a storage site, and finally injecting it into a geological formation. By taking into account the location and specific technology that the CHP would require, both the capital and annual costs of implementing CCS at UMass Amherst have been estimated.

Capturing CO2 from the CHP

Post-combustion carbon capture (PCC) technology using amine-based solvents is currently the most economical option for retrofitting the CHP with CCS. The CHP is both a natural gas combined cycle (NGCC) plant and cogeneration plant. NGCC refers to the fact that the plant uses both a gas turbine cycle (Brayton cycle) and steam turbine cycle (Rankine cycle) to maximize output [34]. The gas turbine generates electricity, and its high-temperature waste heat is used by a heat recovery steam generator (HRSG) to make steam, which then drives a steam turbine (producing additional electricity) [34]. However, the CHP is not an ordinary NGCC plant: as previously mentioned, it is also a cogeneration (combined heat and power) plant. This means that rather than producing only electricity, the plant simultaneously produces heat, allowing it to achieve greater efficiencies than a combined cycle plant without cogeneration [35]. Although there are now many examples of PCC technology being used at NGCC plants, there are few examples of this technology being used at NGCC cogeneration plants. Due to the absence of economic data on NGCC cogeneration plants specifically, available data on regular NGCC plants will be used to approximate the capital and annual costs of implementing the capture technology at the CHP.

First, the capital cost of retrofitting must be estimated. As seen in part 5 of the Appendix, the total capital cost of a retrofitted NGCC plant is about $1,700/kW, whereas the cost of an NGCC plant without PCC technology is about $800/kW [36]. Since the CHP produces a total of 14 MW, the capital cost of retrofitting the CHP would be approximately $13 million [5]. This is just 10% of the original cost of constructing the CHP [37]. Next, the annual costs of the PCC technology must be calculated. In FY 2019, UMass reported about 110,000 MtCO2 emitted from CHP, which represents about 74% of the campus's total CO2 emissions, as seen in Appendix part 1 [16]. Implementing PCC technology has a considerable energy penalty, ranging between

11% to 22% for NGCC plants [38]. This increases the amount of input (fuel) needed by the plant, which in turn leads to increased CO2 emissions. Using an intermediate energy penalty of 16%, this would increase the CHP's emissions to about 125,000 MtCO2 per year, as seen in Appendix part 2. Of these emissions, PCC technology would be able to capture 90%, or about 115,000 MtCO2/year, as seen in Appendix part 3. The price per MtCO2 of avoided carbon at an NGCC plant ranges from $37 to $74, including the cost of compression [38]. Therefore, the low estimate of annual capture and compression costs would be $4.2 million, whereas the high estimate would be $8.5 million, as shown in Appendix part 5. It is likely, however, that the CHP's annual costs would be closer to the lower estimate, due to having a higher thermal efficiency than a normal NGCC plant (55-60% vs. 75% efficiency) [39, 40]. In addition to these capital and annual costs, the "capture readiness" of the CHP must be evaluated.

"Capture readiness" refers to the readiness of a plant for implementation of carbon capture technology, based primarily on spatial considerations and ease of integration with the capture technology [41]. To implement PC technology at a cogeneration plant, there is a high space requirement to hold the absorption and regeneration capture unit, as well as the compression unit. These can require a large plot area, representing acres; one study estimated the size to be similar to the cogeneration layout itself [42]. This requirement can likely be met by the CHP, due to its location in a remote part of campus with potential for expansion. Ease of integration must also be considered. It has been found that PCC technology is integrated particularly efficiently in combined cycle plants, where additional steam can be obtained at the steam turbine outlet [42]. This is very promising, since the CHP features a combined cycle system. Notably, PCC technology was successfully integrated at a commercial level at a combined cycle, gas-fired cogeneration plant in Bellingham, MA. The plant used Economamine FG+ from Fluor, which is a third generation amine-based solvent technology, and captured 330 metric tons of CO2 per day from 1991 to 2005 [43]. Although more information about the availability of space at the CHP site is needed for it to be considered "capture-ready," the Bellingham plant proved that the integration of amine-based PCC technology at cogeneration, NGCC plants like the CHP is feasible.

Carbon Compression before Transportation

After carbon dioxide is captured by the PCC technology, it must be fed into a compressor system to reach the desired pressure for pipeline transportation. To bring vapor CO2 molecules, which naturally exist in a highly disordered fashion with low potential energy, to their supercritical state (> 31℃, > 72atm), which is the state in which CO2 has extremely high potential energy, requires a huge amount of energy. This is especially true in the case of compressing CO2 gas, which exits the amine solvent at about 1 atm (atmospheric pressure), to the desired pressure of at least 150 atm [44]. After being compressed to the supercritical fluid, it then gets pushed vertically into the formation site, which is another compression step. Since it is practically impossible to perform an isothermal compression, CO2 temperature after these compression processes would end up as high as 287°C, much higher than its critical temperature (31°C). With a new system combination of 1:10 low pressure and 1:10 high pressure compressor, and a heat integrated system which can utilize the waste heat generated, the compression process could become less expensive in terms of electricity and energy [44].

The Deerfield and Hartford Basins as Potential Storage Sites

There are several methods of carbon sequestration, each of which comes with different transportation and mechanical needs. At UMass, the most suitable method of carbon sequestration is deep saline aquifers due to the proximity of two sites that show promise in its rock formations: the Deerfield and Hartford Basins [30]. The Deerfield Basin is the closer of the two basins at an estimated four miles from the UMass campus, and is therefore the more promising option [45]. Deep saline aquifers are porous rocks filled with high-salinity water. High-salinity water has a high enough concentration of salt that it is unable to be consumed as drinking water. CCS therefore does not involve contamination of freshwater supply that may otherwise serve as drinking water to a community. In order for this method to work successfully, carbon dioxide is stored about eight hundred meters below ground so that pressure is high enough for CO2 to exist in a dense supercritical liquid state. To prevent it from migrating vertically towards the surface, a caprock or impermeable seal must exist above the aquifer. A similar formation is found in the Deerfield Basin: the Sugarloaf Arkose is a porous rock formation between 1600 meters to 2370 meters thick, with the potential caprock formation being the Fall River Beds that lie above the aquifer. All of the components that make up a successful storage site for carbon dioxide are found in the Sugarloaf Arkose, and its proximity makes this a high possibility for CCS at UMass Amherst.

The cost of carbon sequestration using this method of geological storage varies greatly depending on the characteristics of the basin, such as permeability and reservoir depth, that might affect the rate of CO2 injection [30]. The minimum theoretical CO2 capacities from the two sites are 5 and 125 million MtCO2 for Deerfield and Hartford, respectively [30]. With the annual total capture rate of 115,000 MtCO2, there is enough space to store more than one thousand years of UMass total greenhouse gas. Estimates for basins with similar characteristics to the Deerfield Basin are about $0.55/MtCO2, and if UMass were to monitor the site every five years, the monitoring would cost about an additional $0.03/MtCO2 [46]. The estimated cost to sequester carbon using the deep saline aquifers in the Deerfield Basin would be about $110,000 per year, as seen in Appendix part 8**.** Above the Fall River Beds lies a layer that is known as the Deerfield Basalt that is 120 meters thick, and even more layers of basalt found in the Hartford Basin [30]. Interestingly, another option for carbon sequestration is through deep basalts. Basalts are mineral-rich rock formations that have been proven to absorb carbon efficiently so that it undergoes carbonation to form new carbonate minerals such as calcite [47]. Deep basalt carbon storage is a fairly new technology, and although it is not fully developed, there is potential in the future for UMass Amherst to be able to store its carbon with this up-and-coming technology.

Pipelines: The Best Method to Transport Carbon to its New Home

After selecting a potential geological sequestration site, another major consideration is how to transport the CO2 from the source to the injection site. The two main options for carbon transportation are trucking and piping. However, trucking would entail very high costs over time, as well as significant CO2 emissions. Due to the low pressure tolerance of commercial gas tanks (~15 atm), it would take one gas tank about 195 trips every day to transport all of the CO2 captured annually from the CHP, as seen in Appendix part 6 [48]. This would cost approximately $500,000-$560,000 in gas money per year, assuming that gas prices stay constant at $2.1/L, also shown in Appendix part 6 (although gas prices have dropped recently with the COVID-19 pandemic). These trips would also release about 4 MtCO2 into the air each year, which is counterproductive, since the main goal of CCS is to reduce CO2 emissions [49]. Moreover, the low pressure of the CO2 while it is being transported by truck would necessitate an additional compression facility to be built at the injection site, increasing overall costs. These reasons make trucking unviable as a method to transport CO2 from UMass in the long-term.

Transportation via pipeline, on the other hand, offers a much more practical solution. The CO2 transport cost model by the National Energy Technology Laboratory can be used to estimate both the capital and annual costs of using pipeline transportation at UMass [50]. Given that UMass would need to transport about 115,000 MtCO2 annually, and that the injection site is about 4 miles away, the capital cost (accounting for inflation) of pipeline implementation would be approximately $5.4 million; the annual operating costs would be around $170,000, as seen in Appendix part 7. Although building the pipeline infrastructure presents a high capital cost, it is more cost-effective and environmentally-friendly in the long-term than trucking. Thus, pipelines would serve as the better method of CO2 transportation from the UMass campus.

In order to successfully implement carbon capture and storage at UMass Amherst, many different aspects of implementation must be taken into account, from the integration of post-combustion capture technology at the Central Heating Plant to the sequestration of the captured CO2 in the nearby Deerfield and Hartford Basins. The total capital cost of implementing CCS at UMass was found to be around $18.4 million, mainly due to the cost of retrofitting the CHP and the cost of building a new pipeline (Appendix part 9). The annual costs of implementation ranged from $4.4 million to $8.8 million, for an average of $6.5 million each year (Appendix part 10). Assuming the CHP continues to be in operation for the next 20 years, the overall cost of implementing CCS at UMass would be about $65 per MtCO2 avoided (Appendix part 11). Although this cost is very significant, there are many ways it can be alleviated, as will be discussed in the analysis of the pros and cons of carbon capture.

Chapter 5: Weighing the Pros & Cons of CCS

Implementing CCS technology at UMass's CHP would allow UMass to cut at least 80% of its Scope I and Scope II emissions by 2030, as seen in part 4 of the Appendix, while ensuring the continuation of a stable source of heat and power for the university in order to provide education for thousands of students. To better understand the benefits and challenges of implementing CCS at UMass, as well as who they will impact, the implementation will be evaluated in three respects: economics, environment, and equity. Although its implementation at UMass will have a high capital cost, environmental risks, and some backlash with regard to its equity, CCS is a vital step in mitigating UMass Amherst's carbon emissions.

The Economics of CCS

One of the most challenging aspects of CCS is finding ways to overcome the high cost of implementing the post-combustion carbon capture (PCC) technology at the CHP. This cost involves a capital cost of about \$13.4 million, and a subsequent high annual cost of about \$6.5 million. This annual cost is the result of the high energy intensity required not only to regenerate the amine solvent, but to compress the CO2 as well. However, there is considerable potential to offset this cost. The captured CO2 can be sold to the two biggest CO2 consumers: the fertilizer industry for urea manufacturing, which uses about 130 MtCO2/year, and enhanced oil recovery, which uses 70-80 MtCO2/year [51]. In addition, a new emerging market section called "CarbonTech" includes companies that make high value products such as carbon nanotubes, as well as many materials used in the medical, electronic, and battery industries [52]. Finally, UMass may also be able to offset the costs of CCS due to the recent Bipartisan Budget Act of 2018, which offers a tax credit incentive for carbon capture. Under this Act, UMass may be qualified to receive \$50/MtCO2 for saline storage and \$35/MtCO2 for utilizing the carbon in a qualifying manner [53]. This would provide a revenue of close to \$6 million per year, thus reducing the annual cost of operating PCC to less than \$1 million in the best case scenario (Appendix part 12). One condition that determines UMass's eligibility to receive this tax credit is whether the CHP falls under the category of "facility" or "power plant"; another is whether or not UMass is able to contract a third party to own the CCS equipment. These questions must be posed by UMass and answered by a qualified legal team before the university can receive any form of federal compensation for CCS technology. Therefore, although the costs of CCS appear high on the outset, there are several avenues that can be pursued to make it more economical.

Another considerable economic challenge that must be taken into account is the additional costs incurred by retrofitting. Most estimates of the costs of PCC are based on new plants which were designed to include the carbon capture technology. Retrofitting an existing plant, on the other hand, can be significantly more costly depending on the plant size, age, efficiency, air pollution control systems, and the availability of space to accommodate a capture unit [23]. Fortunately, these higher costs due to retrofitting should be minimal at the CHP for several reasons. Due to its relative youth, the CHP has state-of-the-art technology that enables it to have a very high energy efficiency, which would keep the increase in electric costs due to PCC low. Furthermore, the CHP already has excellent air pollution control systems, which are necessary to filter out NOx and SO2 gases since they would cause rapid solvent degradation; additional scrubbers would need to be installed otherwise. Finally, the fact that the CHP is relatively young also makes it economical to retrofit, as the cost of retrofitting would be lower than the cost of building a new plant with PCC [23]. This may not be true for an older plant nearing the end of its lifespan. For all of these reasons, the CHP is a good candidate in terms of economics for retrofitting with PCC.

CCS and the Environment

There are several environmental advantages that come with CCS, with the most obvious being the reduction of climate-change causing carbon dioxide emissions into the atmosphere. Based on a 90% capture rate and the UMass FY 2019 Emissions Inventory, CCS at the CHP would be able to sequester 80% of overall Scope I and II campus carbon emissions (Appendix part 4). This would present a significant decrease in carbon emissions from the state of Massachusetts as a whole, as the UMass campus is the top state-owned contributor to the state's greenhouse gas emissions [4]. Moreover, as an educational institution, UMass has the chance to become the first successful pioneer with CCS technology. As specified earlier in Chapter 2, renewable energy sources alone cannot feasibly fulfill all of UMass's heating and electricity needs, mainly due to their low efficiencies and the campus's non-optimal location [7, 13]. Numerous other large universities, particularly in the Northeast, face the same issue. Thus, if UMass were to successfully implement CCS and spread the knowledge gained from "learning by doing," then it could inspire other institutions to consider CCS as a practical solution in their own effort to reduce GHG emissions.

Despite these significant environmental benefits, PCC technology also has environmental downsides that must be considered. One of these disadvantages is that the production of monoethanolamine (MEA), which is the main solvent used to separate CO2 from other flue gases, involves both direct and indirect carbon emissions [24]. These increased emissions needed for solvent production can detract from the net efficiency of CCS at reducing carbon emissions. To truly reduce its carbon footprint, UMass would need to acquire the MEA solvent from a source that utilizes "clean energy" for the production process, whether it is by using renewable energy or by using carbon capture technology at the production plant. Furthermore, PCC has the risk of amine-solvent losses from the absorber column of the capture unit, which may lead to amine degradation and the formation of carcinogens such as nitrosamines and nitramines [24]. These can contaminate local water supplies; as a result, solvent mixtures must be carefully chosen to minimize downstream degradation processes.

Although deep saline aquifers are a proven method of carbon sequestration, there are still several environmental concerns that are raised when discussing any form of geological storage. Storage of CO2 in deep saline aquifers occurs naturally, so the injected CO2 would likely remain trapped in the formation for about 1,000 years [29]. Furthermore, the salt concentration of the brine water found in the deep saline aquifers is too high for human consumption, reducing the risk of contaminating freshwater supplies [30]. However, a large environmental concern is the possibility of fractures in the caprock, which may lead to leakage of CO2. The CO2 could then be released into the atmosphere, as well as into the surrounding soil, which would potentially harm plant life and subsoil ecosystems. UMass would then have to fill in these fractures with an artificial impermeable replacement for the caprock, such as cement [29]. This cost should be taken into account when considering CCS. The risk of leakage can be reduced by producing brine from the saline aquifer and reinjecting it a certain distance from the CO2 injection site, which would increase the percentage of CO2 dissolved over 200 years from about 8% to 50% [29]. The production of brine would, however, require more energy and therefore higher costs. Thus, CCS poses several environmental risks; however, its implementation at UMass could serve as an opportunity to conduct more research to reduce these risks, and would aid greatly in the mitigation of carbon emissions overall.

The Equity Considerations of CCS

The impacts of CCS on equity must also be considered. Overall, because it is a new technology that is still being researched, surveys show that the majority of the public are unaware of CCS or skeptical of its ability to mitigate carbon emissions [54]. The transportation and storage of carbon is the most prominent cause for concerns related to the equity of CCS in this case, as the capture and compression of CO2 would take place at the CHP itself. As was previously established in Chapter 4, the Deerfield Basin is the most feasible storage site for the campus's CO2, and is located in the town of Deerfield, MA and extends into Greenfield, MA [55]. In order to assess the potential threat that CCS poses to equity, the demographic composition of these communities was considered, as implementation would have a greater effect on low-income communities than on higher-income ones. Oftentimes, families of low-income communities cannot attend town meetings regarding health and safety due to long working hours, whereas higher-income communities are better able to afford the time and resources to deal with such issues and protect their community. According to the 2018 U.S. Census Bureau, the median household income of Deerfield residents was about $76,000, which is about the average household income in Massachusetts. Over half of the population had received a Bachelor's degree, and over 95% of residents had received a high school diploma [56]. This implies that Deerfield is not a low-income community, and its residents are educated enough to be aware of the environmental and health risks of a project like CCS.

Moreover, it is evident that the town of Deerfield has an active Board of Health that defends its residents' health and safety. In 2014, the Deerfield Board of Health banned the installation of pipelines that would transport natural gas from the Gulf of Mexico to New England [57]. Although this may present a challenge when building pipelines to transport CO2 from UMass to the Deerfield Basin as a potential carbon sequestration site, it is important to note the differences in pipeline usage. The main concern that the Deerfield Board of Health expressed regarding the natural gas pipelines was the need for an onsite compression station, which would have taken 50 to 70 acres of land [58]. However, this would not be a problem with CCS. Furthermore, the health risks that come with transporting fracked gas—contaminated drinking water, the release of air toxins, and explosions of pipelines—are much worse than the risks of transporting CO2 [59]. The transportation and sequestration of CO2 into the Deerfield Basin may receive some backlash, but its actual implementation would pose a limited threat to the equity of the Deerfield residents.

Although carbon capture and storage is far from perfect and has significant drawbacks, these are outweighed by its considerable benefits in terms of economics, the environment, and equity.

Chapter 6: Conclusion

The University of Massachusetts Amherst is the top emitter of carbon in the state of Massachusetts. With the planned expansion of campus, it is vital that the university takes the necessary steps to reduce its carbon emissions to net zero by 2030, per the goal of the Carbon Mitigation Task Force. The reality is that we no longer have the time to delay action in the race against climate change, and CCS offers the best and most realistic solution to meet the goal of net-zero within the given time frame. Although the price to pay may seem high, it is well worth it to ensure a livable climate for generations to come.

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Appendix

1. **Carbon Emissions from the CHP**
   Total campus emissions (includes scopes I, II, and III): **146,427.90 MtCO2**
   Percentage of total campus emissions from CHP: **74%**
   Annual emissions from the CHP: 146,427.90 MtCO2 * 0.74 = **108,357 MtCO2**

2. **Carbon Emissions from CHP with CCS**
   Annual emissions from CHP without CCS: **108,357 MtCO2**
   Increase in emissions from CHP with CCS (due to 16% energy penalty):
   108,357 MtCO2 * 0.16 = **17,337 MtCO2**
   Annual emissions from CHP with CCS: 108,357 MtCO2e + 17,337 MtCO2e = **125,694 MtCO2**

3. **Captured Carbon Emissions by CCS at the CHP**
   Annual emissions from CHP with CCS: **125,694 MtCO2**
   Annual captured emissions from CHP with CCS (assuming 90% capture rate):
   125,694 MtCO2 * 0.90 = **113,124 MtCO2**

   (Note: the 113,124 MtCO2e captured by CCS at the CHP means 113,124 MtCO2e will need to be sequestered.)

4. **Percentage of Campus Emissions Mitigated by CCS**
   Annual emissions captured by CCS: **113,124 MtCO2**
   Annual campus emissions (scopes I and II only): **126,425 MtCO2**
   Annual campus emissions (scopes I and II only) with increase in annual emissions due to CCS: 126,425 MtCO2 + 17,337 MtCO2 = **143,762 MtCO2**
   Percentage of annual campus emissions (scopes I and II only) mitigated by CCS:
   113,124 MtCO2 / 143,762 MtCO2 = **78.7%**

5. **Cost of Retrofitting the CHP with PCC**
   Capital cost of:
   NGCC plant retrofitted with PCC: **$1736/kW**
   NGCC plant without capture: **$780/kW**
   Retrofitting an NGCC plant: ($1736/kW) - ($780/kW) = **$956/kW**
   Retrofitting the CHP: 14 MW * (1000 kW/MW) * ($956/kW) = **$13.4 million**
   Operating cost per MtCO2 avoided at NGCC plant:
   Low estimate: **$37/MtCO2**
   High estimate: **$74/MtCO2**
   Annual operating cost of PCC at the CHP:
   Low estimate: 113,000 MtCO2 * $37/MtCO2 = **$4.2 million**
   High estimate: 113,000 MtCO2 * $74/MtCO2 = **$8.4 million**

Average: ($4.2 million + $8.4 million)/2 = **$6.3 million**

(Note: PCC = post-combustion carbon capture, and includes both the costs of capture and compression.)

6. **Cost of Carbon Dioxide Transportation via Trucking**

Volume available of a 60cbm truck: **60 meter^3**
Density of CO2 at 15 atm and 45°C: **26.86 kg/meter^3**
Average fuel cost in Massachusetts: **$2.1/L gas**
Average fuel consumption of a full-load 60cbm truck: **31.8L gas/100 km**
Average fuel consumption of a empty-load 60cbm truck: **17.6L gas/100 km**
Trucking trips annually:
$\frac{115{,}000MtCO2}{year} * \frac{1000kg}{1Mt} * \frac{1m^3}{26.86kg} * \frac{1trip}{60\,m^3} * \frac{1year}{365\,day}$ = **195.5 trips/day**
Full-load trips cost:
$\frac{195.5trips}{day} * \frac{4mile}{trip} * \frac{1.6km}{mile} * \frac{31.8L\ gas}{100km} * \frac{\$2.1}{1L\ gas}$ = **$835.5/day**
Empty-load trip cost:
$\frac{195.5trips}{day} * \frac{4mile}{trip} * \frac{1.6km}{mile} * \frac{17.6L\ gas}{100km} * \frac{\$2.1}{1L\ gas}$ = **$462.4/day**
Approximate total annual cost, including labor cost (truck driver):
(835.5+462.4)*365 + 60,000 = **$534,000/year**

7. **Cost of Carbon Dioxide Transportation via Pipeline**

Distance from UMass Amherst to Deerfield, MA: **4 miles**
Capital cost of pipeline ($2011): 4 miles * ($4.1 million / 3.5 miles) = **$4.7 million**
Capital cost of pipeline ($2020): 4.7 million * 1.03^9 = **$6.13 million**
Annual operating cost of pipeline ($2011): 4 miles * ($112,000 / 3.5 miles) = **$128,000**
Annual operating cost of pipeline ($2020): $128,000 * 1.03^9 = **$167,010**

(Note: calculations based on FE/NETL CO2 Transport Cost Model, where 3.5 miles of pipeline transport 0.14 million MtCO2 per year for a capital cost of $4.1 million and an annual operating cost of $112,000.)

8. **Annual Cost of Storage**

Median onshore cost of U.S. saline storage ($2003): **$0.5/tCO2**
Monitoring cost assuming five-year intervals ($2003): **$.03/tCO2**
Cost of saline storage & monitoring ($2003): ($0.55 + $0.03)/MtCO2 = $**0.58/MtCO2**
Annual amount of CO2 to be captured from CHP: **115,000 MtCO2**
Annual cost of saline storage ($2003): $0.58/MtCO2 * 115,000 MtCO2 = **$66,700**

Annual cost of saline storage ($2020): \$66,700 * 1.03^{17} = **\$110,244**

9. **Total Capital Cost for CCS Implementation**

   PPC capital cost: \$13.4 million
   Pipeline capital cost: \$4.7 million
   Total Capital Cost: **\$18.4 million**

10. **Total Annual Operating Cost for CCS Implementation**

    PPC annual cost: \$6.3 million
    Pipeline annual cost : \$167,010
    Storage annual cost: \$110,000
    Total Annual Cost: **\$6.57 million**

11. **Total Cost of CCS Implementation (\$ per Metric Ton of CO2 Avoided)**

    $$\left(\frac{\$18.4*10^6}{20\ year}+\frac{\$6.57*10^6}{year}\right)*\frac{1\ year}{115{,}000\ MtCO2}$$= **\$65/MtCO2**

    (Note: assumes a 20-year lifespan for CCS.)

12. **Potential Offset from 45Q Tax Credit**

    Maximum possible annual offset: 115,000 MtCO2 * \$50/MtCO2 = **\$5.75 million**
    Minimal possible total annual cost: \$6.57 million - \$5.75 million = **\$0.82 million**
    Minimal total cost of CCS implementation (\$ per metric ton of CO2 avoided):

    $$\left(\frac{\$18.4*10^6}{20\ year}+\frac{\$0.82*10^6}{year}\right)*\frac{1\ year}{115{,}000\ MtCO2}$$= **\$15/MtCO2**

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