In Situ **Carbon Sequestration Assessment For New York City Power Sources**

Johanna Nelson and Grace Gribbon

July 25th, 2019

1. Introduction

1.1 Carbon dioxide capture and storage through *in situ* carbon mineralization

Carbon capture and storage (CCS) from fossil-fuel electricity generation plants is an effective method for the removal of anthropogenic CO_2 emissions from the atmosphere. [1] CCS is conventionally achieved through the use of saline tanks and CO_2 storage reservoirs that are covered by impermeable rock, in order to prevent release of CO_2 to the surface. [1, 2] Normally, dissolved CO_2 in water is highly buoyant at injection (usually at > 800 m depth); such qualities increase the likelihood of leakage at the surface, leading to potential contamination of shallow-water resources [3]. In recent years, trapping mechanisms have been developed to combat leakage and provide long-term storage [3]. *In situ* carbon mineralization, also known as combined mineral capture and storage, is a recently developed CCS technique where either pure or dissolved CO_2 is injected into porous rock to chemically react and form stable minerals. [3, 4] When the CO_2 is dissolved in water, it forms weak carbonic acid which can then form bicarbonate ions after reacting with carbonate or silicate minerals. Solid carbonates are finally formed when these bicarbonate ions further react with minerals found in various rock types. The rocks most advantageous for this process are basalt and peridotite, due to their containment of minerals such as olivine, pyroxenes, serpentine, plagioclase and basaltic glass [3].

A successful implementation of carbon sequestration through *in situ* carbon mineralization in basaltic rock exists at the Hellisheiði Geothermal Power Station in Iceland [5]. The pilot project, known as CarbFix, focused on injecting a mixture of captured CO_2, H_2S, and H_2O into wells of porous basaltic lava 400-800m below ground, where it naturally reacts with the basalt underground and forms solid carbonate minerals [6]. The CarbFix Pilot project began in 2006 and has taken over a decade to establish a successful carbon sequestration process with basalt [6]. Almost all H_2S was mineralized after fourth months of injection, and over 95% of the injected CO_2 was mineralized within a year [6]. The general methodology prior to development included the complete scope and characterization of the subsurface system, determination of where rejected carbon ends up through identification of reactive/non-reactive tracers, and modeling basalt-CO2 interaction in a laboratory setting to determine the result prior to implementing it in the field [6].

Other cases of carbon sequestration using *in situ* carbon mineralization exist in the United States; for example, the Wallula project in Washington State was the second successful implementation of this technology. The project involved the injection of 977 tons of dissolved CO_2 828-886 meters below ground [4]. Researchers studied the area for several years, and they did not observe CO_2 leakage; it is unknown how much of the CO_2 formed minerals [4]. Other small-scale work that has been done on the subject includes research by Daniel Northaft on the Staten Island Serpentinite [2]. Northoft's undergraduate thesis on the subject was mentored by Professor and researcher on carbon sequestration Peter Kelemen at Columbia University. Some of the methods used by Northoft are used in this paper.

1.2 Feasibility of *in situ* technology

The high cost of carbon capture and storage is largely due to the lack of technological experience and research on the application; this lack of research is caused by the incentives given to fossil fuel industries. The opportunities for injection of CO_2 for oil recovery far surpass those of carbon mineralization [4]. Despite these current limitations, *in situ* methods in particular are cost-competitive because of its advantage of providing permanent carbon storage with little risk of leakage [4]. The total cost of the CarbFix Pilot project, 12 million EUR, exemplifies this financial advantage because it is two to four times cheaper than conventional CCS methods [6]. Current cost estimates are between $38-143/ton of CO_2 stored for conventional CCS, while it is only $25/ton of CO_2 for CarbFix methods [15].

In order to replicate the carbon sequestration seen at Hellisheiði in Iceland, there are parameters to consider: the availability of abundant H2O, the adequate flow/outlet potential in subsurface, and the integrity of the rock in order to keep the CO2 safely stored underground for years [7]. Additionally, sequestration sites can potentially be located onshore or offshore. An application similar to that of CarbFix is optimal for CO2 storage located offshore, below the seafloor, due to the ample amount of porous basalt and seawater present [6].

Along the eastern United States coastline, in the Central Atlantic Magmatic Province (CAMP) basalts formation, multiple potential onshore and offshore sequestration sites are present [8]. Confirming the feasibility of potential sites is done by collecting geophysical and drill core data. One of the potential sites is the Newark Rift Basin, which contains low-permeability Orange Mountain basalt, with a 15% porosity value average [8]. Modeling studies have suggested basalt present under two other basins, the Sandy Hook and New York Bight basins [8]. The New York Bight basin, found along Long Island, has an area of over 1000 km^2 and contains >800m of sediments. [8]. The Sandy Hook basin, located in New Jersey, is considerably smaller, with an average bulk porosity of 15% and 900 Mt of CO_2 volume for injection space [8]. Although no samples have yet been extracted from these sites, the collection of field data as well as investigation into cost-effective pilot projects at these sites would further the assessment of carbon sequestration potential and feasibility. Through geologic storage of CO_2 at these sites, ultimately 1000s of trillions of tons can be stored [4].

1.3 Thesis

The construction of a CO2 sequestration system, as part of a coal or oil plant located in the New York tri-state area, will prove to be economically, socially, and physically feasible in tandem with the technology used in the Carbfix project in Iceland.

2. Methods and Data

2.1 Determining Potential Sequestration Sites and Power Plants

We determined potential *in situ* carbon sequestration site locations through contact with Columbia University professor Dr. David Goldberg. We asked Dr. Goldberg for his recommendations concerning *in situ* potential and locations in the New York area. Goldberg recommended choosing onshore and offshore locations from Goldberg et. al. (2010) to limit potential sites to those meeting the geological requirements of implementing CarbFix technology [8]. We chose the three basins with the closest proximity to New York City: the Newark Rift basin, Sandy Hook basin, and New York Bight basin (see Figure 2). The Newark Rift and Sandy Hook basins have onshore storage site potential while the New York Bight basin has offshore storage potential [8].

In order to determine the five highest carbon emitting power plants sourcing New York City's energy, we catalogued data from The Commission for Environmental Cooperation's 2016 power plant emissions report [9]. See Figure 1 for the locations of these five power plants in relation to New York City. After pulling the emissions data from the five power plants, we narrowed our selection to three plants by evaluating their annual CO_2 emissions and optimal transportation feasibility (see Table 1). The average of the distances from a given plant to each basin site determined the transportation feasibility of each power plant (see Table 1). The three power plants chosen to be further evaluated were the Northport Power Station in Long Island and the Ravenswood and Astoria Generating Stations in Queens. For the purposes of this paper, we prioritized annual emissions over transportation feasibility for determination of power plants. For example, we included Northport, as the highest emitter, despite it having the worst transportation feasibility (i.e. the highest average distance). We ranked Ravenswood and Astoria second and third in possessing the highest emissions and optimal transportation feasibility. We did not choose the East River Station, despite having the best transportation feasibility (i.e. the lowest average distance), because it possessed the second lowest annual emissions.

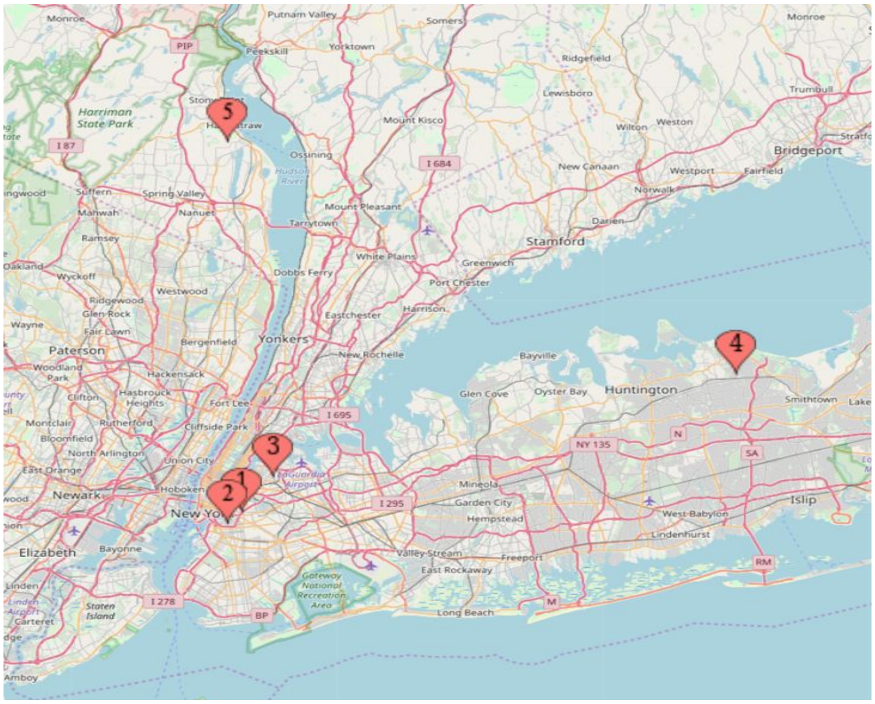

Figure 1: Five Potential Power Plants to Assess. 1) Ravenswood, 2) East River, 3) Astoria, 4) Northport, 5) Bowline Point. Original Figure.

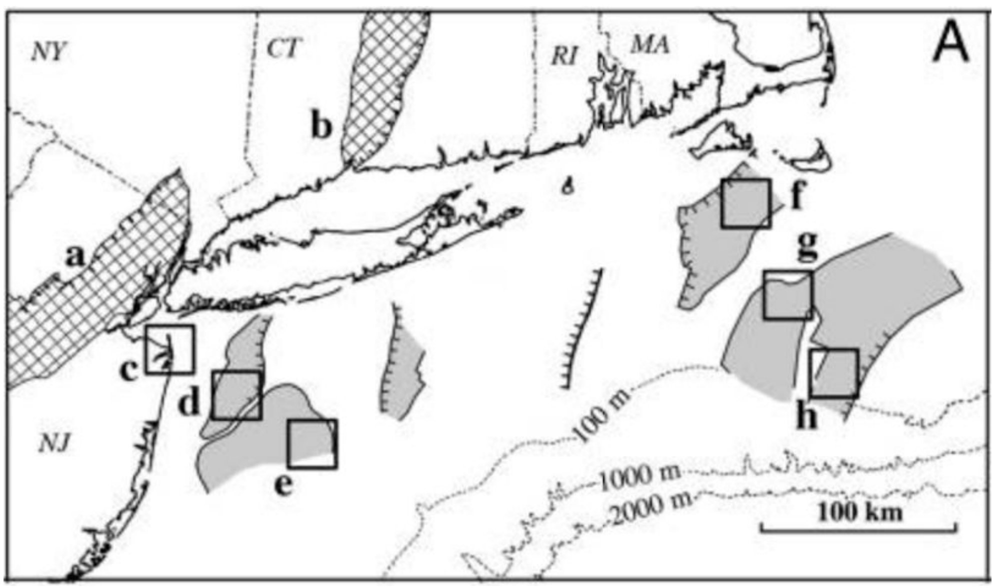

Figure 2: Locations of potential carbon sequestration sites. Sites chosen for the purpose of this paper are a) Newark Rift Basin c) Sandy Hook basin, d-e) New York bight basin. Source: Kelemen et. al. (2015)[8]

2.2 Measuring Sequestration Site Potential

Prior to comparison of the impact of using different sequestration sites with the chosen power plants, sequestration site potential was quantified by calculating carbon storage capacity of each. We used the formula from Northaft (2015), used previously to estimate the maximum

CO_2 capacity of Staten Island Serpentinites (see Formula 3). We broke down the sites down into six cases due to the little likelihood the entire surface of the basin would have been drilled for carbon sequestration.

We designated three cases for the Newark Basin: low, high, and overall potential. We found values for low and high potential from the range of carbon storage results in Collins et. al. (2017) [11]. We included these values in addition to the overall potential of the basin (calculated using Formula 1) to show the difference of using the entire basin versus only portions of the basin. We assigned Sandy Hook with only one case because a specific value for it total CO_2 sequestration potential was given in Goldberg, et. al. (2010) [8]. We assigned the last two cases as low and high potential for the New York Bight Basin. We based these potentials on different depth measurements – 500 m for low potential and 3 km for high potential – to show the case for shallowest carbon storage and deepest carbon storage. We calculated the values for New York Bight basin potential using Formula 3. We used Google Earth to measure the surface area of the New York Bight basin, since no specific surface area data for the basin was publicly available.

We used the carbon storage capacity values from Section 3.1 to determine the number of years possible for each sequestration site to store the total emissions for the case of each power plant. Formula 3 divided a sequestration site's carbon capacity by a power plant's annual emissions to calculate the number of years of complete carbon storage.

Power Plant	**Annual CO2 emissions**	**Transportation feasibility**
1. East River	1,375,180.33	Distance to Newark site: 22 km Sandy Hook: 38 km NY Bight: 27 m Sum of distances: 87 km **Average distance: 29 km**
2. Astoria	3,189,821.02	Newark: 51 km Sandy Hook: 111 km NY Bight: 27 km Sum of distances: 189 km **Average distance: 63 km**
3. Ravenswood	3,458,795.84	Newark: 53 km Sandy Hook: 97 km NY Bight: 32 km Sum of distances: 182 km **Average distance: 61km**
4. Northport	5,023,285.66	Newark:: 107 km Sandy Hook: 167 km NY Bight: 62 km Sum of distances: 336 km

		Average distance: 112 km
5. Bowline Point	1,028,981.30	Newark: 61 km Sandy Hook: 96 km NY Bight: 83 km Sum of distances: 240 km **Average distance: 80 km**

Table 1: The five highest emitting power plants in New York City are listed with their respective annual emissions (t) and calculated transportation feasibility.

2.3 Assessment of Social Savings

The social cost of carbon (SCC) is defined as the monetized value of damages from the release of one ton of carbon into the atmosphere [13]. We conducted the social savings calculations based off two different values for the social cost of carbon: $40 and $200. We noted $40 as the current average social cost of carbon used in the United States [13]. We noted $200 as the value more generally accepted by current researchers, and the monetary value cited in the *Expert Consensus on the Economics of Climate Change* [14]. We completed all social savings calculations twice for these two SCC values.

Formulas 1-3 determined a clear environmental assessment of the power plants before and after implementing the *in situ* carbon sequestration. Formulas 1 and 2 specifically evaluated the positive and negative social costs.

2.4 Comparison of Conventional CCS versus CarbFix Costs

Our fourth calculation stressed the difference in costs between implementing conventional carbon capture and storage and CarbFix technology. We used Formula 4 to complete this comparison between the potential power plants.

Formula 1
[Power Plant CO2 Emissions/yr] x [SCC] = Negative Social Cost from Emissions/yr

Formula 2
[Potential CO2 Storage of Sequestration Site] x [SCC] = Positive Social Cost from Emissions/yr

Formula 3
[Potential CO2 storage of site] ÷ [emissions/yr] =Years of Potential Storage for Power Plant

Formula 4
[Cost/ton of storage] x [Power Plant Emissions] = Total Implementation Cost

3. Results

3.1 Carbon Storage Capacity Calculations

We determined the carbon storage capacities of the three sequestration sites, for six cases, by using Formula 1 (see Table 2 and Figure 3). The case with the highest storage capacity was the Newark Basin, since it had the largest surface area. For further calculations and figures, we excluded the overall potential of the Newark Basin because its large surface area did not allow for logical comparisons with the cases focusing on lower levels of potential in the sequestration sites. We determined the largest storage capacity range was the New York Bight basin, with a range of 14.9-895 Gt CO_2. The Newark basin had a considerably smaller range, 1.9-20.2 Gt CO_2, and the Sandy Hook basin had the smallest value of 0.9 Gt CO_2 potential.

Although an initial reaction might be to prefer the New York Bight Basin over other sequestration sites, we realized these numbers were considerably large compared to those of the emissions of an average power plant. In comparison, the CarbFix pilot project (Iceland) had an estimated basalt reservoir CO_2 sequestration potential of 0.33 Gt CO_2 at the CarbFix site (Iceland) [12]. Additionally, Goldberg put the 0.9 Gt CO_2 potential of the Sandy Hook basin into context by stating its equivalence to the emissions of three or four 1-GW coal-fired power plants for forty years [8].

	Newark Basin Low Potential	Newark Basin High Potential	Newark Basin Overall Potential	Sandy Hook	NY Bight Low Potential	NY Bight High Potential
Surface Area (km^2)	6.1e+9	6.1e+9	6.1e+9	8	663	663
Storage Capacity (Gt CO_2)	1.9	20.2	2090	0.9	14.9	895

Table 2: Carbon Storage Capacity for Sequestration Sites. Original Table.

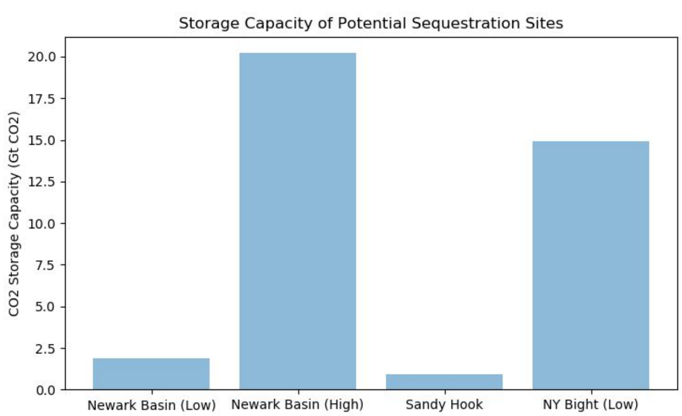

Figure 3: Storage Capacity of Potential Sequestration Sites. Original Figure.

3.2 Future Carbon Storage Calculations

From the carbon storage potential calculations, we calculated the number of years of complete carbon storage using Formula 2 (see Figure 4). Identical to the trends in Section 3.1, the Sandy Hook Basin had the lowest number of years and the New York Bight basin had the highest number of years across all power plants. We did not intend for these numbers to be an indicator of how the sequestration sites would be used, since such an indicator would mean that 100% of emissions from the power plants are trapped and sequestered into the basins. Instead, we meant for these values to represent how much storage the sequestration sites can hold in comparison to the CO_2 emissions of the power plants. When compared to the annual emissions of the power plants assessed in this paper, the potential of sequestration site storage was astronomically large.

Power Plant	Newark Basin Low Potential	Newark Basin High Potential	Sandy Hook (900 Mt Potential)	NY Bight Low Potential (Depth = 0.5 km)
Northport	378	4021	179	2966
Ravenswood	549	5840	260	4307
Astoria	595	6332	282	4671

Table 4: Years of Storage (Combinations Between Sequestration Sites and Power Plants)

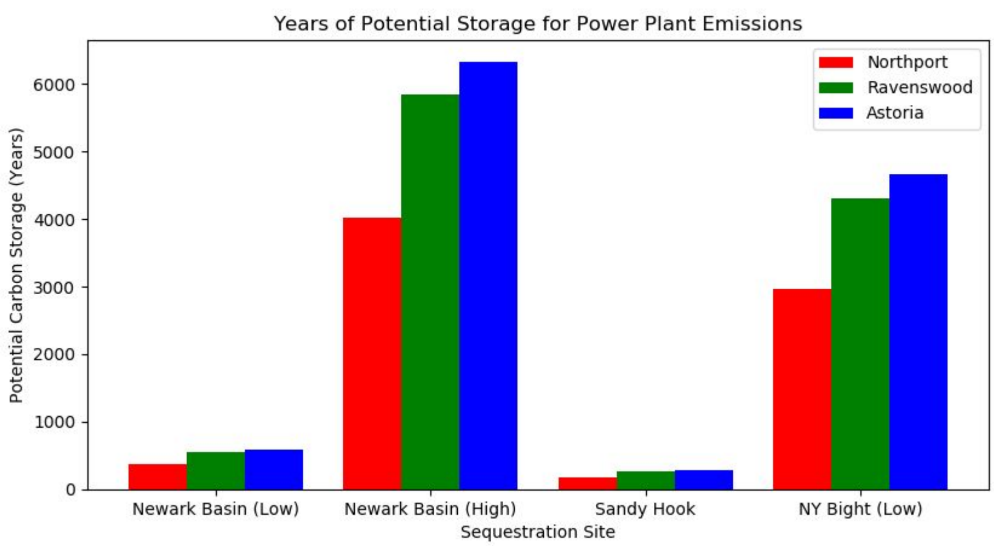

Figure 4: Years of Potential Storage for Power Plant Emissions. Original Figure.

<u>3.3 Social Cost Calculations</u>

Based on two social costs of carbon (the choices of $40 and $200 are explained in Section 2.3), we calculated two types of overall social costs: an annual negative social cost related to the carbon emissions emitted by the power plants, and a positive social cost related to the carbon emissions avoided through the sequestration sites. As expected, the negative social costs were considerably larger when determined from the more scientifically accepted value (of $200 than the more widely used $40). The power plant with the largest negative social cost was Northport and the power plant with the smallest negative social cost was Astoria (see Table 3 and Figure 5). As compared to the annual negative social costs, the positive social costs of using the sequestration sites were over one thousand times larger (see Table 4 and Figure 6).

Just as we meant the results in Table 2 to illustrate the size of the sequestration site potential, we meant these monetary values to illustrate the amount of environmental damage that could be avoided versus the yearly environmental damages that take place as a result of individual power plant emissions.

	Negative Social cost/yr where SCC = $40 (SCC * emissions) (US $/year)	**Negative Social cost/yr where SCC = $200 (SCC * emissions) (US $/year)**
Northport	200,931,426	1,004,657,000
Ravenswood	138,351,834	691,759,200
Astoria	127,592,841	637,964,200

Table 3: Annual Negative Social Cost of Power Plant Emissions

	Newark Basin Low Potential	Newark Basin High Potential	Sandy Hook	NY Bight Low Potential
Annual Social Positive Cost (SCC = $40) (US $)	76,000,000,000	808,000,000,000	36,000,000,000	596,000,000,000
Annual Social Positive Cost (SCC = $200) (US $)	1.52E+22	1.616E+23	7.2E+21	1.192E+23

Table 4: Positive Social Cost of Using Full Potential of Sequestration Sites

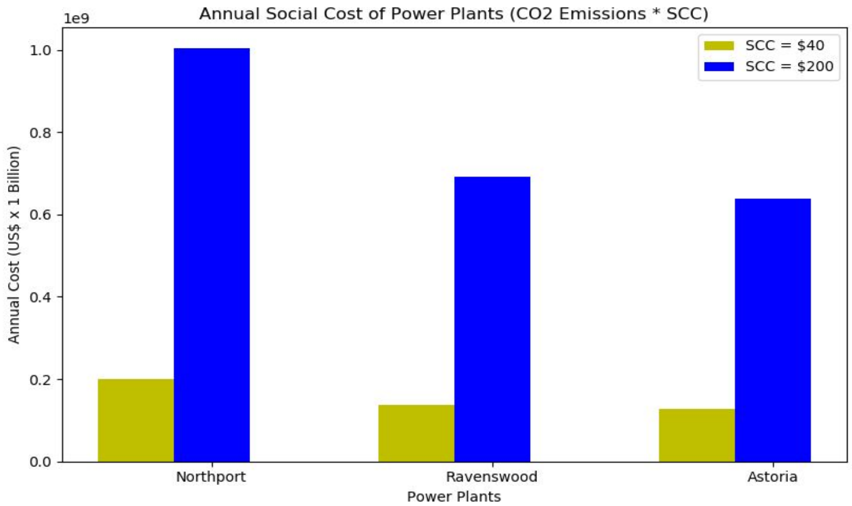

Figure 5: Annual Negative Social Cost of Power Plants. Original Figure.

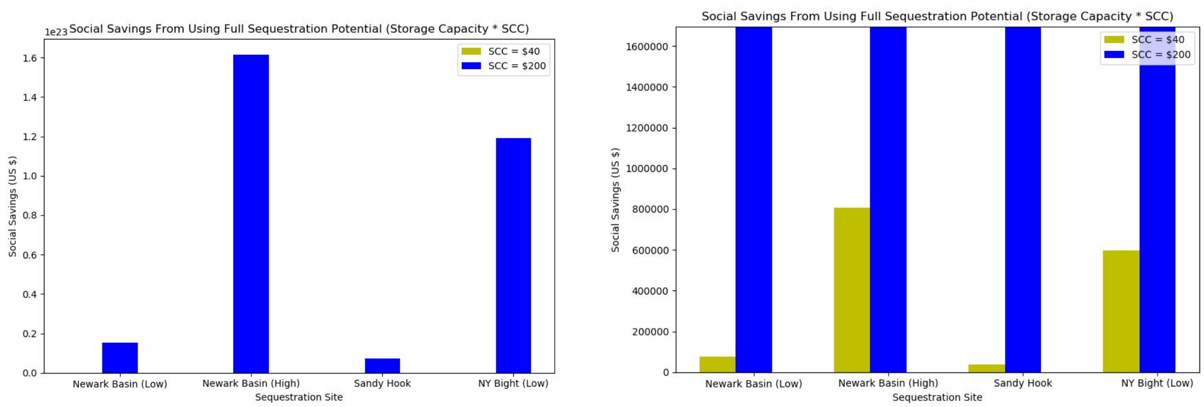

Figure 6: Positive Social Cost of Sequestration Sites. Original Figure. Left image: zoomed-out image. Right image: zoomed-in image to show the SCC = $40 values. Original Figure.

3.4 Annual Cost Calculations Based on CarbFix

We calculated and then compared the costs of using CarbFix technology and using conventional carbon capture and storage, per ton of CO_2 stored. We found that the cost of storing one ton of carbon using conventional carbon capture and storage is between $120-140, whereas the cost of storing one ton of carbon using CarbFix technology is only $25. When we multiplied these two values by the total emissions of each power plant, we determined a clear advantage with using CarbFix technology. Therefore, in addition to the more symbolic social costs, this concrete cost clearly showed the financial advantage of choosing to use CarbFix technology.

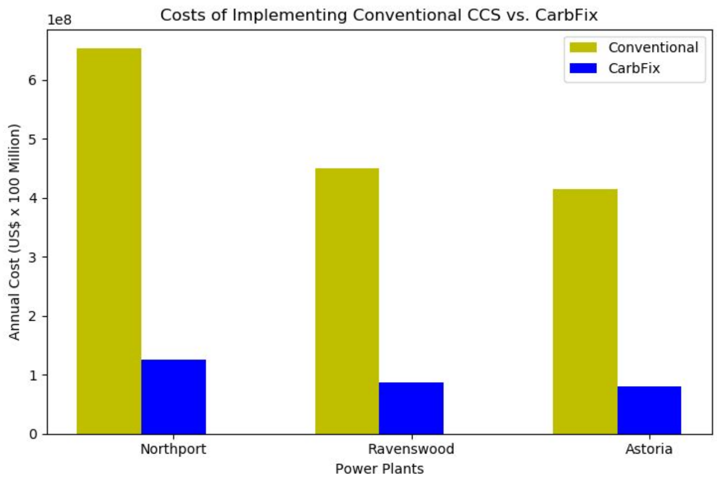

Figure 7: Comparison of costs of implementing CarbFix technology and conventional carbon capture and storage. Original Figure.

3.5 Additional Qualitative Considerations (onshore vs. offshore)

The final parameter that we considered in choosing optimal power plants and sequestration site pairings was the advantages of using offshore sites over onshore sequestration sites. In Goldberg, et. al. (2010), he gave a preference of using offshore sites such as the New York Bight basin because of the lesser chance of injection leaks during the sequestration process. [8] He cited the onshore site case of Hellisheiði in Iceland, specifically, since its injection wells had led to some overpressure and induced seismicity. He explained that with offshore sites, there was unlimited reservoir for the required water during the sequestration process [8].

3.6 Choosing Optimal Power Plants and Sequestration Sites

See Table 5 for a summary of the different parameters discussed and calculations made to determine optimal sequestration sites and power plants. Choosing a single optimal power plant and sequestration site pairing was difficult to do because of the quantity of parameters we researched. Instead, we chose to name multiple sites as optimal for different reasons. For example, the Astoria Generating Station had the most years of potential storage and was therefore the best long-term option with any sequestration site. The Newark Rift Basin had the largest storage capacity, so it was most desirable for any short-term power plant sequestration project. The New York Bight basin was the only offshore sequestration site that we focused on, so it had the advantage of avoiding the leaks that occur at onshore sites. See other highly ranked power plants and sequestration sites in Table 5.

Rank	**Sequestration Site Parameters**	Surface area	Positive Social Cost	Offshore/ Onshore	**Power Plant Parameters**	Distance	Emissions	Negative Social Cost
1 (highest)		Newark	Newark	NY Bight (offshore)		Ravenswood	Northport	Astoria
2		NY Bight	NY Bight	Newark Sandy Hook (onshore)		Astoria	Ravenswood	Ravenswood
3 (lowest)		Sandy Hook	Sandy Hook			Northport	Astoria	Northport

Table 5: Ranking of Power Plants and Sequestration Sites Based on Qualitative and Quantitative Parameters.

<u>**Discussion**</u>

Despite not detecting a single, optimal project for sequestering the CO_2 emissions of a power plant near New York City, we collected data that relates to the economic, environmental, and physical feasibility of any project that could potentially happen between the discussed locations. These findings, therefore, can be used in the future as a starting point for proposing a sequestration project. Energy companies looking to invest and do pilot tests could easily do so, knowing what advantages the different pairings have based on Table 5.

Future research in multiple areas of this paper is necessary to have a wider view of the potential for creating a sequestration site in the tri-state area. For example, a cost benefit analysis between different power plants and sequestration sites would give a concrete idea of the financial feasibility of investing in such a project. We were unable to find annual cost data for different power plants, since this data is unavailable online and attempted contact proved unhelpful. A cost benefit analysis would likely have results more preferable than one done for conventional capture and storage technology, based on Figure 7.

Additionally, further field work and pilot projects relating to the geology of the basaltic basins discussed in this paper needs to occur before these results can be taken to a development phase. In smaller cases, such as the Staten Island serpentinite findings by Northaft (2015), the researchers successfully collected data confirming the presence of basaltic formations required for *in situ* carbon mineralization technology [2]. A similar step would need to be taken with the Newark Rift, Sandy Hook, and New York Bight basins before any actual projects go into a proposal phase.

Conclusion

Based on our findings, we conclude that it is feasible to apply *in situ* carbon mineralization technology to sequestration sites near New York City, for the sake of lowering the emissions of nearby power plants. The results from our measured parameters show the (1) financial advantage of CarbFix technology as opposed to conventional CCS, (2) the environmental savings that would be made through actualizing positive social costs, and (3) the physical feasibility of developing the sequestration sites in terms of their long-term storage potential. Rather than presenting a single, optimal potential sequestration site to develop for a specific plant, there are multiple sites that are advantageous when different parameters are prioritized. In the future, an energy company could choose to develop a specific project depending on which parameters they want to prioritize in their proposal.

Our results directly support the findings in Goldberg, et. al (2010) as well as the mission of the CarbFix 2 Project [8][11]. We presented the potential for power plants that can feasibly be paired with the sequestration sites (supported by Goldberg). Our results also support further research in this field and the development of more specific plans for creating a sequestration site in the tri-state area. In relation to CarbFix 2, the potential for such applications of *in situ* carbon mineralization should be explored through proposing specific projects. These proposals can use specific parameters discussed in this paper depending on what is prioritized when developing the project. If such parameterization of power plants and sequestration sites is done throughout different regions with the required geological formations, this would allow for easier development of more sequestration projects. In the context of a larger renewable energy transition, this project prioritized long-term environmental considerations by highlighting the substantial carbon emission reduction with the implementation of this technology. The shift towards both renewable energy and carbon sequestration is not only economically feasible but of undeniable necessity in order to lower the externalities caused by carbon in the future.

References

[1] Matter JM, Stute M, Snæbjörnsdottir SO (2016) Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. Science. Doi: 10.1126/science.aad8132

[2] Nothaft D (2015) Carbon dioxide sequestration in the Staten Island Serpentinite. Columbia University.

[3] Kelemen PB, Matter JM (2009) Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation. Nature Geoscience. doi: 10.1038/ngeo683

[4] Malik JAN (2019) US Academies call for research agenda on Negative Emissions Technologies and Reliable Sequestration. MRS Bulletin 44:13–15. doi: 10.1557/mrs.2019.6

[5] Aradóttir ESP, Sonnenthal EL, Björnsson G, Jónsson H (2012) Multidimensional reactive transport modeling of CO2 mineral sequestration in basalts at the Hellisheiði geothermal field, Iceland. International Journal of Greenhouse Gas Control. doi: 10.1016/j.ijggc.2012.02.006

[6] Aradóttir ESP, Gíslason SR, Oelkers EH, Sigurdardóttir H (2018). A brief history of CarbFix: Challenges and victories of the project's pilot phase. Energy Procedia. doi: 10.1016/j.egypro.2018.07.014

[7] Kelemen PB, Matter JM (2009) Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation. Nature Geoscience. doi: 10.1038/ngeo683

[8] Goldberg DS, Kent DV, Olsen PE (2010) Potential on-shore and off-shore reservoirs for CO2 sequestration in Central Atlantic magmatic province basalts. Proc Natl Acad Sci U S A. doi:10.1073/pnas.0913721107

[9] Commission for Environmental Cooperation. In: NORTH AMERICAN POWER PLANT - AIR EMISSIONS. http://www.cec.org/sites/default/napp/en/country-profiles/united-states/emissions/carbon-dioxide.php. Accessed 25 Jul 2019

[10] J. D, Collins (2017) Characterization of the Triassic Newark Basin of New York and New Jersey for geologic storage of carbon dioxide. In: Characterization of the Triassic Newark Basin of New York and New Jersey for geologic storage of carbon dioxide (Technical Report) | OSTI.GOV.

https://www.osti.gov/biblio/1368193-characterization-triassic-newark-basin-new-york-new-jersey-geologic-storage-carbon-dioxide. Accessed 25 Jul 2019

[11] (2017) The CarbFix 2 project. In: www.or.is. https://www.or.is/en/projects/carbfix/news/carbfix-2-project. Accessed 25 Jul 2019

[12] Callow B, Falcon-Suarez I, Ahmed S, Matter J (2018) Assessing the carbon sequestration potential of basalt using X-ray micro-CT and rock mechanics. International Journal of Greenhouse Gas Control 70:146–156. doi: 10.1016/j.ijggc.2017.12.008

[13] The true cost of carbon pollution. In: Environmental Defense Fund. https://www.edf.org/true-cost-carbon-pollution. Accessed 25 Jul 2019

[14] Maréchal K (2013) The Economics of Climate Change and the Change of Climate in Economics. doi: 10.4324/9780203117668

[15] Gunnarsson I, Aradóttir ES, Oelkers EH, et al (2018) The rapid and cost-effective capture and subsurface mineral storage of carbon and sulfur at the CarbFix2 site. International Journal of Greenhouse Gas Control 79:117–126. doi: 10.1016/j.ijggc.2018.08.014