As Americans continue to drive bigger cars and use more energy to fuel their technologically enhanced lifestyles, the emission of greenhouse gases into the atmosphere has dramatically risen. One of these gases, carbon dioxide (CO_2), has particularly harmful effects when present in high concentrations, including deterioration of the ozone layer. For this reason, scientists are developing new ways, such as carbon dioxide sequestration, to combat carbon dioxide emission.

Carbon dioxide sequestration is the process of permanently storing CO_2 underground, in the ocean, or as biomass. These three methods are known as geological, oceanic, and terrestrial sequestration, respectively. Within geological sequestration there are three main processes: storage in depleted oil and gas reservoirs, storage in deep saline formations, and storage in unmineable coal beds. Our model evaluated the relative benefits of these five carbon capture and storage methods.

The advantages of each method were divided into three different categories: economic efficiency, carbon storage potential, and environmental and societal impacts. Each method received three rankings, one from each category, that were then combined to determine a preferability coefficient. Our model can be used to compute the yearly consumption rates for each method of sequestration, favoring those with higher preferability coefficients. In order to create a practical model, constraints were placed on the yearly consumption rates of each method, limiting them to what is technologically feasible.

Our model evaluated three scenarios that projected either the cost of carbon neutrality, the maximum capacity given the proposed 2009 budget, or the sequestration rates needed to maximize preferability. The results of our model showed that carbon neutrality is not fiscally possible. However, our model can be used to make recommendations that maximize carbon sequestration rates and minimize environmental impact within the parameters of the budget.

Carbon sequestration is a relatively new process that is becoming more extensively researched. As more data is collected, the calculations in the model can be adjusted to make more accurate predictions for the future.

<u>Statement and Analysis of Problem</u>

As the consumption of fossil fuels has drastically increased over the past decades, the global population has become more concerned with the concentration of carbon dioxide (CO_2) in the atmosphere. Coupled with the transition to alternative fuels and decreased consumption, carbon sequestration is an essential step in reducing the net carbon emission each year. Carbon sequestration can be separated into three main methods: terrestrial, geological, and oceanic.

Terrestrial sequestration is the conversion of CO_2 into biomass through the process of photosynthesis. While terrestrial sequestration is a natural process, it can be enhanced by afforestation and proper land management. The second method, geological sequestration, permanently stores CO_2 underground. Although carbon can be sequestered into different underground regions, our model focuses only on the three areas with the most potential: depleted oil and gas reservoirs, deep saline formations, and unmineable coal beds. Ocean sequestration occurs naturally at the surface of the ocean but at a very slow rate. Like terrestrial sequestration, oceanic sequestration can be enhanced, in this case by injecting carbon dioxide into the ocean at depths of 3,000 meters or lower. Currently oceanic sequestration is the least developed of the three different methods. However, ocean sequestration is receiving more research because scientists speculate that the ocean will eventually absorb at least 80% of CO_2 in the atmosphere.[1]

[1]Okun and Glazer, http://www.princeton.edu/~chm333/2002/fall/co_two/oceans/

Discussion of Variables

Our model focused on optimizing CO_2 sequestration with minimal economic and cultural impact. To do so, we evaluated each method based on three different categories: cost, total capacity to store CO_2, and environmental benefits and risks. Each sequestration method received three ratings based on its advantages and drawbacks in the three categories. The economic rating, E, favors more cost efficient methods, while the sequestration potential, S, favors methods with the highest storage capacity, and societal rating, C, favors the safest, most environmentally conducive methods. These three ratings were finally combined to create one coefficient, P, or the preferability coefficient, that ranked the five methods to optimize their overall advantages.

Economic Impact

Each of the five sequestration methods received an economic rating that combined both the total cost of sequestration and any economic benefits that offset the cost. The cost estimates were based on researched values. Terrestrial sequestration costs \$13.7/ton CO_2 sequestered. The other four methods are more expensive because they require the capture, transportation, and the storage of the carbon dioxide. Oceanic sequestration costs \$46.5/ton, while each of the geological methods costs \$60/ton. Based on available data, we assumed that the cost between each geological method was not significantly different.

Sequestration into depleted oil and gas reservoirs can be used combined with a technology called enhanced oil recovery (EOR) to extract oil more efficiently and offset the cost of carbon storage. Because each ton of carbon sequestered increases oil recovery by $12.21, the net cost of sequestration into oil and gas reserves is $47.79/ton. Similarly, sequestration into unmineable coal beds is used with a technology called enhanced coalbed methane recovery (ECMR) to produce $5.59 of methane per ton of carbon, making the new cost of sequestration into unmineable coal beds $54.41/ton. The economic rating was found by converting the cost/ton into tons/$100 and then standardized so the highest rating was five and the others followed proportionately.

Table 1: Cost for Each Method

Variable	Method	Cost[2]
M_T	*Terrestrial Sequestration*	$13.7
M_O	*Oceanic Sequestration*	$46.5
M_R	*Geological Sequestration in Depleted Oil and Gas Reserves*	$47.79
M_S	*Geological Sequestration in Deep Saline Formations*	$60
M_C	*Geological Sequestration in Unmineable Coal Seams*	$54.41

Table 2: Economic Rating for Each Method

Variable	Method	Economic Rating[3]
E_T	Terrestrial Sequestration	5.00
E_O	Oceanic Sequestration	1.47
E_R	Geological Sequestration in Depleted Oil and Gas Reserves	1.53
E_S	Geological Sequestration in Deep Saline Formations	1.14
E_C	Geological Sequestration in Unmineable Coal Seams	1.26

[2] Please see Appendix Table 1
[3] Ibid.

Sequestration Potential

The sequestration potential was calculated for each of the methods by dividing the total storage capacity by the total number of CO_2 emissions per year. If all the CO_2 emissions were hypothetically concentrated into one method, the number calculated above would estimate how many years it would take for the source to be completely filled. We standardized the scores so that the highest sequestration potential rating was five and the rest followed proportionally.

Because terrestrial capacity is a renewable source, there is not a finite total capacity. However, there is a yearly maximum sequestration rate. Based on the yearly sequestration rate of 926 million tons of CO_2 per year, we calculated the total consumption of carbon dioxide through terrestrial sequestration after 816 years.[4] We assumed that this estimation realistically represents the capacity of terrestrial sequestration relative to the other methods.

Table 3: Sequestration Potential for Each Method

Variable	Method	Sequestration Potential[5]
S_T	*Terrestrial Sequestration*	2.37
S_O	*Oceanic Sequestration*	5.00
S_R	*Geological Sequestration in Depleted Oil and Gas Reserves*	0.28
S_S	*Geological Sequestration in Deep Saline Formations*	3.18
S_C	*Geological Sequestration in Unmineable Coal Seams*	0.54

[4] Please see Appendix Calculations for Detailed Explanation of Estimates.
[5] Please see Appendix Tables 2 and 3

Societal Impact

We took into consideration the benefits and risks of each method in regards to the environment. We assessed the benefits of each process on a scale of 1 to 5, with 1 being the least beneficial and 5 being the most beneficial. We gave terrestrial sequestration a score of 5 because it improves forest health, creates new wildlife habitats, and increases the recreational value of lands. The other four methods were assigned societal ratings of 1 because they have no significant environmental benefits.

The second component of the societal impact rating is the risks of each method. We gave each method a safety score of three and subtracted points proportionate to the drawbacks of each process. Oceanic sequestration had a high risk value because the method slightly lowers the pH of the surrounding water, disrupting local ecosystems. Geological sequestration methods were given medium risk values because of the possibility of leakage. We distinguished between the three geological processes based on their relative depth, where the shallowest presented the most danger. Terrestrial sequestration received the lowest risk value because the only drawback is competition among the plants. All of these values were assigned to qualitative data, and our model assumes that they accurately represent the importance of each impact.

Table 4: Societal Impact Rating for Each Method

Variable	Method	Societal Impact Rating [6]
C_T	*Terrestrial Sequestration*	5.00
C_O	*Oceanic Sequestration*	0.67
C_R	*Geological Sequestration in Depleted Oil and Gas Reserves*	1.00
C_S	*Geological Sequestration in Deep Saline Formations*	2.00
C_C	*Geological Sequestration in Unmineable Coal Seams*	1.33

Preferability Coefficient

The preferability coefficient, P, is the sum of the economic rating, the sequestration potential, and the societal rating and is used to evaluate the overall advantages of each method. In combining these scores, we assumed that each rating has an equal importance. For this reason, each score was previously adjusted to a standard five point scale. The calculation of P is illustrated in the equation below.

$$P_n = E_n + S_n + C_n$$

Table 5: Preferability Coefficient for Each Method

Variable	Method	Preferability Coefficient
P_T	*Terrestrial Sequestration*	12.37
P_O	*Oceanic Sequestration*	7.14
P_R	*Geological Sequestration in Depleted Oil and Gas Reserves*	2.81
P_S	*Geological Sequestration in Deep Saline Formations*	6.32
P_C	*Geological Sequestration in Unmineable Coal Seams*	3.13

[6] Please see Appendix Table 5

<u>Development of Model</u>

Our model was designed to find the amount of CO_2 that should be sequestered per year using each method. The amount of CO_2 sequestered for each method is defined as the yearly sequestration rate. The total sequestration rate is the sum of the individual sequestration rates for each method.

$$Q_{Total} = Q_T + Q_O + Q_R + Q_S + Q_C$$

Table 6: Sequestration Rate Variable for Each Method

Variable	Meaning
Q_{Total}	*Total Yearly Sequestration Rate*
Q_T	*Yearly Terrestrial Sequestration Rate*
Q_O	*Yearly Oceanic Sequestration Rate*
Q_R	*Yearly Geological Sequestration Rate for Depleted Oil and Gas Reserves*
Q_S	*Yearly Geological Sequestration Rate for Deep Saline Formations*
Q_C	*Yearly Geological Sequestration in Unmineable Coal Seams Rate*

The purpose of the model was to manipulate each Q_n to maximize the preferability score, Z, of a given scenario. The preferability score is influenced by the proportion of Q_{Total} that is dedicated to each sequestration method. A higher Z-value indicates a scenario that favors sequestration methods with higher preferability coefficients. The calculation of Z is shown below.

$$Z = \frac{P_T Q_T + P_O Q_O + P_R Q_R + P_S Q_S + P_C Q_C}{Q_{Total}}$$

Without any other variables, maximizing Z occurs by simply sequestering all CO_2 using the terrestrial process. However, this is not realistic, primarily because the maximum Q_T is estimated at only 926 million tons of CO_2 per year. In order to account for feasibility, our model introduces another variable, T_n, or technological capacity, that limits Q_n to a realistic value. T_n is determined by which stage of development each method has reached. Our model therefore assumes that each maximum Q_n is proportionate to the development stage of each method. In other words, the most developed technology, geological sequestration in depleted oil and gas reservoirs, will account for the most carbon sequestration, while the least developed process, oceanic sequestration, will only contribute a small amount to the total carbon stored each year. Because terrestrial sequestration is a fully developed, marketable process, the constraint T_T was calculated using the known maximum Q_T instead of the estimated proportion. After adding the limitations T_n, our model could determine the sequestration rates Q_n that are feasible based on current technology.

Table 7: Calculated Technological Capacity Constraints

Variable	Method	Value (maximum Q_n/Q_{Total}) [7]
T_T	*Terrestrial Sequestration*	0.14
T_O	*Oceanic Sequestration*	0.1
T_R	*Geological Sequestration in Depleted Oil and Gas Reserves*	0.5
T_S	*Geological Sequestration in Deep Saline Formations*	0.35
T_C	*Geological Sequestration in Unmineable Coal Seams*	0.25

[7] Please see Appendix Table 7

Our model can also be used to minimize the cost for a specific Q_{Total} or maximize Q_{Total} given a set cost. The total cost per year, or M_{Total} is found using the following equation.

$$M_{Total} = M_T Q_T + M_O Q_O + M_R Q_R + M_S Q_S + M_C Q_C$$

The calculations of our model rely on the algorithms provided by Microsoft Excel's equation solver. The target cell varies between our three optimization variables: Q_{Total}, Z, and M_{Total}. In the adjustable cells, the solver computes the amount of sequestration that should be invested in each method, Q_n. The T_n constraints described above limit the maximum for Q_n.

Application of Model

We applied our model to three different situations. Scenario 1 evaluated the possibility of neutrality – matching carbon emissions with an equal rate of carbon sequestration. Thus, for this situation Q_{Total} was set at 6,596 million tons of CO_2 per year, the 2007-2008 rate of carbon emission.[8] The minimum cost calculated using our model while still maintaining this rate of carbon consumption was $294.6 billion per year. Given the speculated 2009 U.S. Department of Energy budget for carbon sequestration, $149 million[9], it is not economically feasible to obtain neutrality. The Z-value given for this situation was 4.70.

[8] U.S. Department of Energy, www.eia.doe.gov
[9] DOE Chief Financial Advisor, http://www.cfo.doe.gov/budget/09budget/Content/Volumes/Volume7.pdf

Table 8: Summary Statistics of Scenario 1- Minimum Cost while Maintaining Neutrality

Variable	*Value*
Z-value	4.70
M_{Total}	\$294.6 billion
Q_{Total}	6,596 billion tons CO_2 per year

	Sequestration Rate (billion tons CO_2 per year)
Q_T	923.4
Q_O	659.6
Q_R	3,298
Q_S	659.6
Q_C	1,649

In Scenario 2 we estimated the maximum Q_{Total} while limiting M_{Total} to the speculated 2009 carbon sequestration budget. Scenario 2 projected a maximum Q_{Total} of 3.34 million tons of CO_2 per year. Like Scenario 1, this situation dealt only with cost and yearly sequestration rate and was not influenced by the preferability coefficient. Scenario 2, therefore had the same preferability score of 4.70.

Table 9: Results Summary of Scenario 2 – Maximum Yearly Sequestration Rate on a Fixed Budget

Variable	*Value*
Z-value	4.70
M_{Total}	\$149 million
Q_{Total}	3.34 million tons CO_2 per year

	Sequestration Rate (million tons CO_2 per year)
Q_T	0.467
Q_O	0.333
Q_R	1.67
Q_S	0.334
Q_C	0.833

In Scenario 3 we used our model to estimate the maximum preferability score, Z_{max}, with M_{Total} still limited to the 2009 budget. The Q_{Total} for this scenario, 3.16 million tons of CO_2 per year, was slightly lower than that of Scenario 2. However, the Z-value of 5.81 for Scenario 3 was significantly higher than the Z-value of 4.70 for Scenarios 1 and 2. The values Q_n in the table below show how carbon sequestration should be divided between the five different methods in order to achieve Z_{max}.

Table 10: Results Summary of Scenario 3 – Maximum Preferability Score on a Fixed Budget

Variable	*Value*
Z-value	5.81
M_{Total}	$149 million
Q_{Total}	3.16 million tons CO2 per year

	Sequestration Rate (million tons CO_2 per year)
Q_T	0.442
Q_O	0.316
Q_R	1.30
Q_S	1.11
Q_C	0.00

Evaluation and Recommendations

The strengths of our model include the ability to maximize different variables. Our model also incorporates feasibility through budget and technological constraints, both of which can be adjusted for future analysis. However, because of the limited data available on the topic, the constraints of our model were based largely on estimations. The influence of these hypothesized constraints on the results is a weakness that should be acknowledged. Many of the ratings assigned in our model were numerical values that represented our interpretation of qualitative data. This subjective analysis is yet another weakness.

Our model was designed to evaluate the feasibility of neutrality based on the current situation. Given the speculated economic budget, our model shows that carbon consumption equaling carbon emission is not fiscally possible. Because neutrality is not realistic, achieving Z_{max} given the set budget is of next highest concern. Scenario 3 has the highest Z-value out of the three situations and best optimizes the advantages of the five sequestration methods. Thus we recommend the U.S. adopt the parameters projected in Scenario 3.

All three scenarios that we modeled included the constraints T_n. This inhibited the concentration of carbon consumption in the sequestration methods that were most cost efficient and provided the most storage potential. Oceanic sequestration was notably limited because of the lack of current research. However, it provides the most carbon storage capacity and is cheaper than the three geological methods. Because future research can overcome the constraints T_n, the U.S. should focus research on the sequestration methods with the highest preferability constants. If this is accomplished, more carbon can be consumed through oceanic sequestration, making the entire CO_2 sequestration process more efficient. While there is a huge future for research and development in carbon dioxide sequestration, none of the sequestration methods have the potential to infinitely consume carbon dioxide. Carbon dioxide sequestration can only be used as a temporary solution to balance carbon dioxide emissions.

Appendix

Table 1: Cost of Each Method and Cost Coefficient

	Terrestrial	Oceanic	Oil and Gas Reservoirs	Saline Rock Beds	Unmineable Coal Seams
Capture		45.00	45.00	45.00	45.00
Transportation					
Storage	13.70	1.50	15.00	15.00	15.00
EOR (Enhanced Oil Recovery)	0.00	0.00	-12.21*	0.00	0.00
ECMR (Enhanced Coalbed Methane Recovery)	0.00	0.00	0.00	0.00	-5.59*
Total	13.70	46.50	47.79	60.00	54.41
Tons/$100	7.30	2.15	2.23	1.67	1.84
Weighted Cost Rating	**5.00**	**1.47**	**1.53**	**1.14**	**1.26**

*Values taken from Figure 1

The Tons/$100 values were calculated by dividing $100 by the total cost of each method. The Cost Rating was calculated by converting the tons/$100 values to a scale of 5 by dividing those values by 1.46.

Figure 1: Cost of Different Sequestration Methods

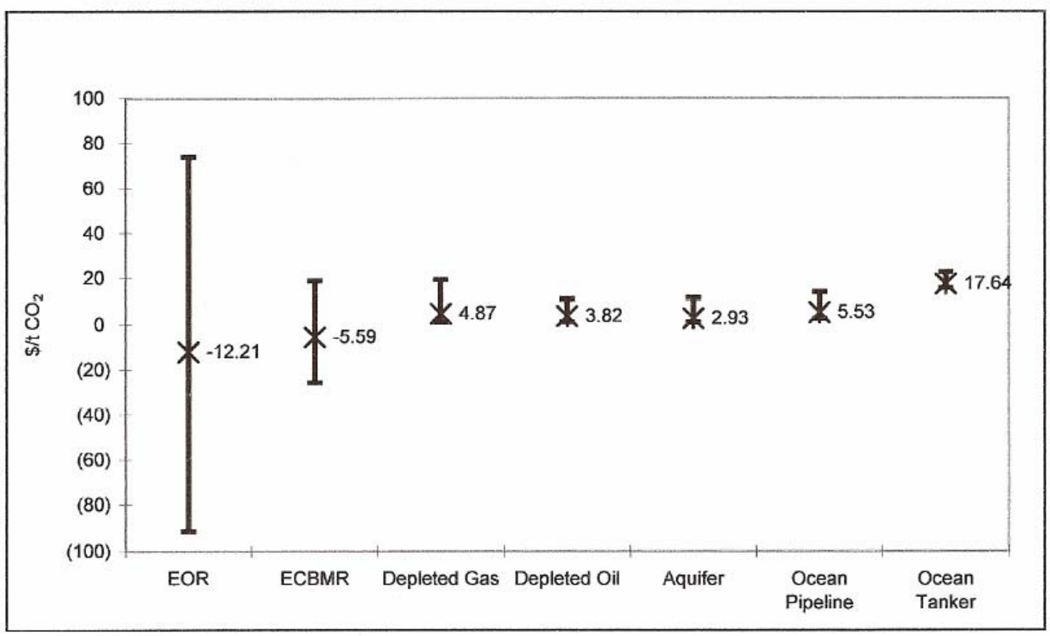

Figure 6. Range of costs for various carbon storage technologies on a greenhouse gas avoided basis.

Table 2: Terrestrial and Oceanic Yearly Sequestration Rate

	Terrestrial	Oceanic
Sequestration Rate per year	925,941,500	1,960,000,000

Table 3: Sequestration Potential

	Terrestrial	Oceanic	Oil and Gas Reservoirs	Deep Saline Formations	Unmineable Coal Seams
Sequestration Capacity	755,870,612,245	1,600,000,000,000	90,900,000,000	1,014,000,000,000	172,600,000,000
Number of Years Until Source Exhaustion	114.60	242.00	13.78	153.70	26.16
Sequestration Potential	2.37	5.00	0.28	3.18	0.54

Table 4: Total Carbon Dioxide Emissions per year (2007-2008)

Total Emissions
6596000000

To calculate the terrestrial sequestration capacity, we divided the oceanic sequestration capacity by the oceanic sequestration rate per year. Then we multiplied the number of years by the terrestrial sequestration rate per year to obtain the terrestrial sequestration capacity. The Number of Years Until Source Exhaustion was calculated by dividing each of the sequestration capacities by the total carbon dioxide emissions per year. The sequestration potential was calculated by converting the number of years until source exhaustion values to a scale of 5 by dividing those values by 48.4.

Table 5: Societal Impact Ratings

	Terrestrial	Oceanic	Oil and Gas Reservoirs	Saline Rock Beds	Unmineable Coal Seams
Environmental Benefits	5.00	1.00	1.00	1.00	1.00
Subtracted Risks	-0.50	-3.00	-2.50	-1.00	-2.00
Safety Score	3.00	3.00	3.00	3.00	3.00
Environmental Impact Coefficient	7.50	1.00	1.50	3.00	2.00
Societal Impact Rating	5.00	0.67	1.00	2.00	1.33

To avoid negative ratings, each method received an initial safety score of three. Since each received the same value, the safety score did not have an effect on the overall value. Each method also received a value for its positive aspects and a value for its negative aspects on a scale of one through five. The societal impact ratings were calculated by converting the environmental impact values to a scale of 5 by dividing those values by 1.5. The highest societal rating is most desired.

Table 6: Preferability Score

	Terrestrial	Oceanic	Oil and Gas Reservoirs	Saline Rock Beds	Unmineable Coal Seams
Cost Rating	5.00	1.47	1.53	1.14	1.26
Sequestration Potential	2.37	5.00	0.28	3.18	0.54
Societal Rating	5.00	0.67	1.00	2.00	1.33
Preferability Score	12.37	7.14	2.81	6.32	3.13

The preferability score is calculated by adding the cost rating, sequestration potential, and societal rating for each method.

Table 7: Technological Capacity

	Terrestrial	Oceanic	Oil and Gas Reservoirs	Saline Rock Beds	Unmineable Coal Seams
Technological Capacity	0.14	0.10	0.50	0.35	0.25

The terrestrial sequestration technological capacity was determined using the known maximum sequestration rate of 925 million tons CO_2 per year. Thus, terrestrial sequestration could only consume 14% of the 6,956 million tons CO_2 of carbon emissions. The technological capacity for the other four sequestration methods was determined based on the current stage of development for each specific method. The stages of development are outlined in Figure 2 below. We then estimated a constraint for each method that was proportionate to the development progress shown in the chart.

Figure 2: Development Stages for Sequestration Methods

Table TS.1. Current maturity of CCS system components. An X indicates the highest level of maturity for each component. There are also less mature technologies for most components.

CCS component	**CCS technology**	**Research phase** [a]	**Demonstration phase** [b]	**Economically feasible under specific conditions** [c]	**Mature market** [d]
Capture	Post-combustion			X	
	Pre-combustion			X	
	Oxyfuel combustion		X		
	Industrial separation (natural gas processing, ammonia production)				X
Transportation	Pipeline				X
	Shipping			X	
Geological storage	Enhanced Oil Recovery (EOR)				X[e]
	Gas or oil fields			X	
	Saline formations			X	
	Enhanced Coal Bed Methane recovery (ECBM)[f]		X		
Ocean storage	Direct injection (dissolution type)	X			
	Direct injection (lake type)	X			
Mineral carbonation	Natural silicate minerals	X			
	Waste materials		X		
Industrial uses of CO_2					X

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