THE SUMMARY

To the United States Congress,

We would like to share with you the results of our study on how to address the nation's carbon footprint. The reduction of CO_2 is crucial because it greatly contributes to global warming, ocean acidification, and interference with other natural processes. We were asked to undertake this endeavor by finding a way to increase carbon dioxide consumption and sequestration. Through our research, our team has developed a model that incorporates many sub-models, each of which addresses CO_2 consumption in a different manner.

Currently, 5.984 billion metric tons of CO_2 is emitted into the atmosphere by the US. About one third of this is already consumed by the biosphere, leaving us with approximately 4 billion metric tons of CO_2 to consume in order to reach carbon neutrality.

Our first sub-model deals with terrestrial sequestration. By planting trees in all available brownfields in the nation and by requiring every household to fill half of their yards with hardwood trees, 288,337,260 metric tons of CO_2 can be sequestered. The total cost of planting these trees amounts to $2,031,841,294. Implementing land-management methods, such as decreasing summer fallow, growing certain crops, and practicing no-till farming, can also significantly increase terrestrial sequestration of CO_2 by 380 million metric tons. These methods achieve this by increasing the amount of CO_2 the soil can sequester. These changes do not require significant amounts of money or social alterations.

A second sub-model is a recently developed concept known as Green Freedom (GF). This model proposes that the US invests in ten $6.9 billion GF plants which convert CO_2 to gasoline using much more energy- and cost-efficient methods than previously implemented. These GF plants will generate a profit that is proportional to the cost of gasoline. For the first year, the plants are expected to produce $2.55 billion. Profits from the existing GF plants will be used to invest in a new GF plant whenever they amass to enough to construct another GF plant. Currently, the amount of money the United States allocates for environmental/alternative energy research and development is not sufficient for implement the entirety of this model in one year.

The third sub-model also deals with recent technology: the development of algae farms to produce biofuel. Algae consume significantly more CO2 per acre than other crops, such as oil palm, corn, and soybeans, which are currently widely used to produce biofuels. However, unlike these crops, algae require concentrated CO2 levels to maintain its rapid growth speed. Thus, to minimize transportation costs of CO2 from power plants, algae farms in our model will be constructed in lands close to existing power plants. Land is available to construct 1,500,000 acres of algae farms which will consume 303.5 million metric tons of CO2 per year and produce 28.35 billion in profit from the biofuel per year.

The fourth sub-model concerns carbon capture and storage mechanisms. CO2-EOR, an enhanced oil recovery method that pumps CO2 into oil reservoirs and helps recover oil by making it more viscous allows 240 billion gallons of "trapped" oils to be retrieved yearly, generating $\$3.282 \times 10^{11}$ in profits, while storing 149.756 mmt of CO2. ECMR ejects CO2 into coal seams which cause the emission of methane gas from the coal. That methane can be captured and sold, generating $\$2.36 \times 10^{14}$ in revenues per year.

In conclusion, we recommend that the US Congress seriously consider the suggestions that we have made. We believe that our model will be effective in addressing this crisis by increasing carbon dioxide consumption and bringing the country closer to national carbon neutrality.

Sincerely, The Research Team

I. INTRODUCTION

Problem Restatement

Due to global warming, its universal implications, and the large extent to which the United States has exacerbated this crisis, the U.S. has become increasingly conscious of its national carbon footprint. It has taken specific actions that are related to decreasing carbon dioxide (CO_2) emissions and increasing CO_2 consumption, also known as carbon sequestration. Our objective is to create a model that increases carbon sequestration to the point at which carbon neutrality is reached, assuming that the amount of emissions is indefinitely limited to that of 2007-2008. In other words, the amount of CO_2consumed by the model should balance the amount of CO_2 emitted. Additionally, our objective is to discover if neutrality is feasible in terms of cost, cultural impact, and effectiveness.

Variables

In the most basic terms, our variables can be simplified to one independent and one dependent variable. The independent variable: the method used to consume CO_2. The dependent variable: the amount of CO_2consumed (in million metric tons (mmt)).

II. ASSUMPTIONS (there are additional assumptions specific to different parts of our model)

1. All CO_2 produced by power plants is available for use.
2. Unless otherwise specified, the CO_2 that is consumed is in Standard Temperature and Pressure.
3. The amount of atmospheric CO_2 stays relatively stable, despite the increase of CO_2 sequestration. This remains as such due to CO_2 sinks, such as the ocean.
4. All citizens, especially farmers and power plant owners, are compliant with the government's requests for change.

III. TERMINOLOGY

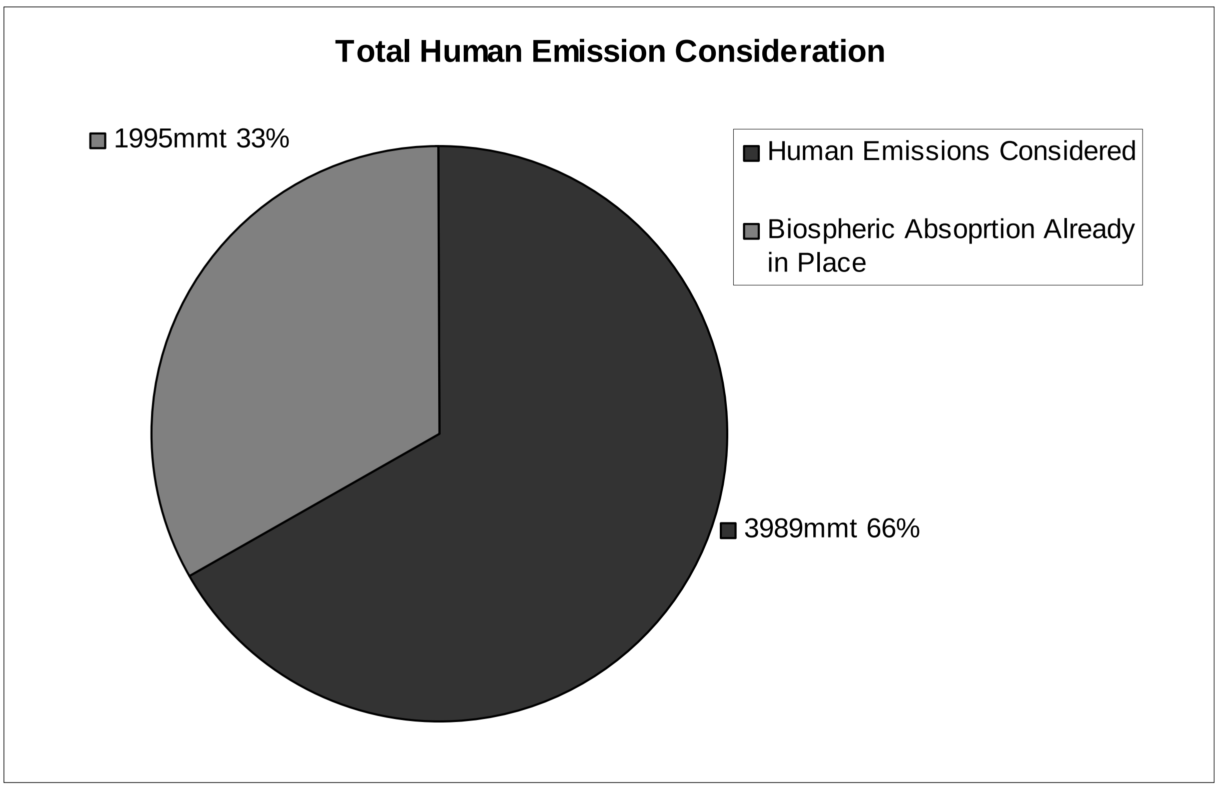
- Biofuel: fuel that is derived from renewable biological resources (biomass)
- Power plant emissions: CO_2 emissions from power plants that can be easily controlled and harnessed
- Atmospheric emissions: other human CO_2 emissions that end up in the atmosphere because they cannot be as easily controlled, monitored, or harnessed (i.e. car exhaust, forest fires, human respiration, etc.)

IV. REASONING AND MODEL

Our model consists of four sub-models that implement various methods of carbon sequestration that all increase emitted CO_2 consumption. The application of all four sub-models will achieve national carbon neutrality. All four of our sub-models operate through carbon sequestration~~,~~ and are defined as follows:

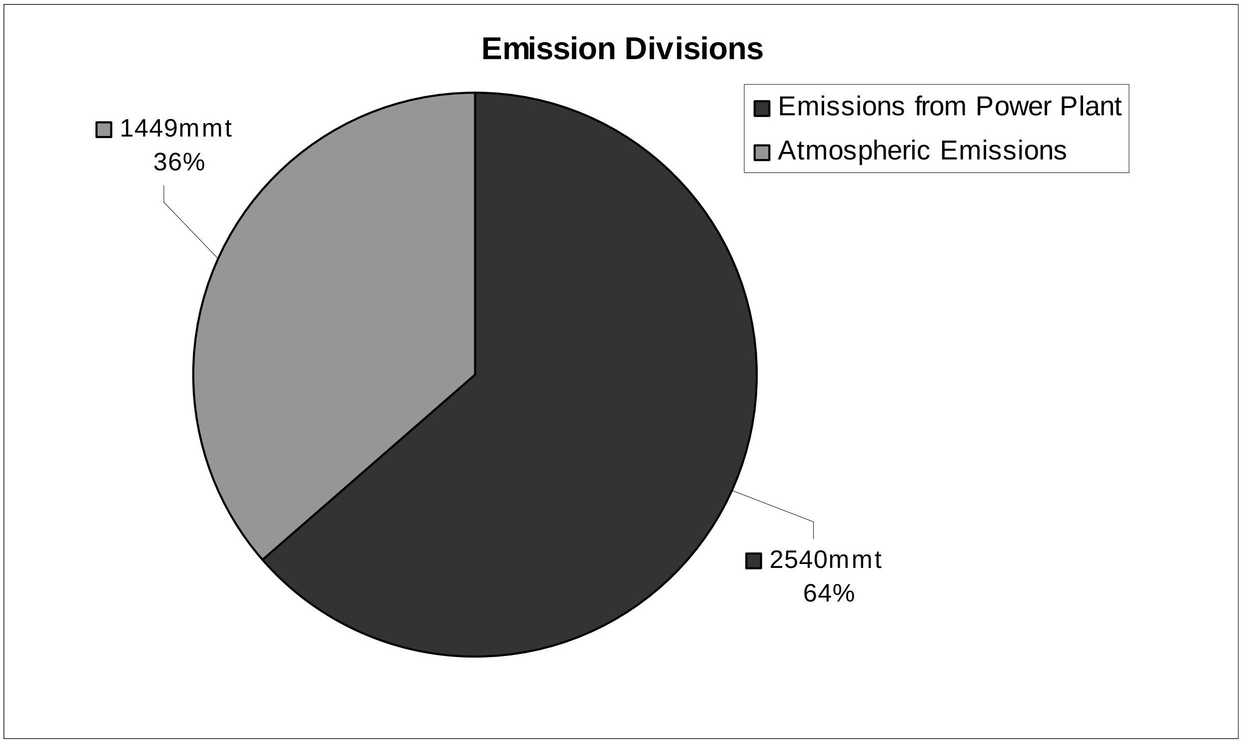
1. Terrestrial sequestration (two parts: planting hardwood trees and increasing soil productivity through land management practices). The CO_2 consumed in this sub-model is harnessed directly from the atmosphere.
2. Green Freedom Technology. The CO_2 consumed in this sub-model is harnessed directly from the atmosphere.
3. Building algae-based biodiesel factories. The CO_2 consumed in this sub-model is harnessed directly from power plants.
4. Carbon Capture and Storage into geologic formations (geo-sequestration). The CO_2 consumed in this sub-model is harnessed directly from power plants.

In 2007, humans emitted 5,984 mmt of CO_2. We found through research that the biosphere absorbs approximately one third, or (5,984 mmt)(1/3) = 1,995 mmt, of emitted CO_2. Thus, (5,984 mmt – 1,995 mmt) = 3,989 mmt. This means that to achieve national carbon neutrality, we must develop a model that consumes 3,989 mmt of CO_2. This is illustrated in Graph 1 (see below).



Graph 1

Of the 3,989 mmt of CO_2 emitted, some are done so by power plants while others are considered atmospheric emissions. We found that in 2007, power plants emitted 2,540 mmt. Thus, 1,449 mmt were atmospheric emissions. It is necessary to differentiate between the two different types of emissions because some carbon sequestration methods use CO_2 extracted from power plants while others use CO_2 extracted from the atmosphere. This is illustrated in Graph 2 (see below).



Graph 2

<u>First sub-model: Terrestrial sequestration</u>

Our first sub-model consists of two general methods of carbon sequestration: planting more trees and implementing land management practices that will increase the amount of CO_2 that soil can absorb.

Assumption for the first method of terrestrial sequestration: the water needed to sustain hardwood trees is paid by the household and is not a responsibility of the government. This will be referred to later.

Planting more trees throughout the US will consume CO_2 via the Calvin Cycle of photosynthesis. We chose to plant hardwood trees for several reasons. First, hardwood trees, compared to other species, grow relatively fast, thus consuming a great amount of CO_2 per a given period a time. Second, hardwood trees are relatively dense, so they can store a lot of CO_2 per cubic meter. Third, hardwood trees grow in a range of sizes, so they can be planted in a variety of settings. The average hardwood tree consumes 48 lbs, or .02177 metric tons, of CO_2 per year~~,~~ and takes up an average of 60 square feet. Finally, hardwoods are very low maintenance, so it would take less money to care for them.

Next, we decided that within the US, hardwood trees can be planted in mass in two different types of settings: Brownfield lands, which are arable areas of land that are currently unused, and in yards of homes.

There are 425,000 sites of Brownfield land in the US. Each Brownfield land ranges in size from 5-15 acres, so each Brownfield land has an average of 10 acres. Thus, (425,000 sites)(10 average acres) = 4,250,000 acres of Brownfield land in all of the US. We converted acres into square feet: (4,250,000 acres)(43,560 square feet / acre) = 1.85×10^{11} ft^2. Given that an average hardwood tree requires 60 square feet to be planted, we found the number of hardwood trees that can be planted in all the Brownfield lands: (1.85×10^{11} ft^2)(1 tree / 60 ft^2) = 3,085,500,000 trees. Each tree consumes an average of .02177 metric tons of CO_2 per year, so: (3,085,500,000 trees)(.02177 metric tons) = 67,171,335 metric tons of CO_2 will be consumed by the hardwood trees planted in US Brownfield lands.

The average land space of a home (including both the actual house and the yard) is 9,100 square feet. The average house is 2,349 square feet, so: 9,100 ft^2 – 2,349 ft^2 = 6,751 ft^2 = the average yard space per home. This may seem larger than a typical yard, but it's an average that includes both homes with no yard and farms that consist of huge fields. Again, since each hardwood tree requires 60 square feet, (6,751 ft^2)(1 tree / 60 ft^2) = 112.5 trees can be planted per home. We also realized that most yards would already have a few trees planted and a portion of yard space may be infertile, so it is unrealistic to assume that all 112.5 trees can be planted. Therefore, we arbitrarily divided that number in half: 112.5 trees / 2 = 56.3 trees, which we rounded down to 56 trees to be planted per home. Since there are 126,316,187 homes in the US, (126,316,187 homes)(56 trees / home) = 7,073,706,472 hardwood trees will be planted in yards. Each hardwood tree consumes an average of .02177 metric tons of CO_2, so (7,073,706,472 trees)(.02177 metric tons) = 153,994,590 metric tons of carbon dioxide by hardwood trees planted in yards.

Thus, 67,171,335 metric tons of CO_2 consumed by hardwood trees to be planted in Brownfield lands + 153,994,590 metric tons of CO_2 consumed by hardwood trees to be planted in yards of homes = 221,165,925 metric tons of CO_2 consumed through our first sub-model of hardwood trees.

We found that it costs approximately \$.20 per hardwood tree seed. Thus, (3,085,500,000 trees planted in Brownfield + 7,073,706,472 trees planted in yards)(\$.2 / tree) = \$2,031,841,294 to plant all the hardwood trees. As previously stated, we assume that there is no additional maintenance cost after the planting of the trees.

The second method of our terrestrial sequestration sub-model includes applying land management practices to increase the productivity of soil in terms of CO_2 absorption. The first agricultural option is no-till or reduced-till farming, which simply means not turning the soil before the seeds for the crops are planted. By not disrupting the soil, previously stored CO_2 in the soil is not released into the atmosphere and more CO_2 can sink into the soil. This land management method sequesters carbon. It is also beneficial to farmers because it reduces soil degradation, decreases fuel and labor costs, and conserves rich organic nutrients in deeper levels of the soil.

The second agricultural option is diversifying crop rotation. By using the land to grow multiple types of crops and not only one, carbon content in soil increases, and is thus sequestered. This option also benefits farmers because it prevents the growth of insects, disease, and weeds.

The third agricultural option is reducing soil erosion. There are several ways of doing this. For example, decreasing summer fallow decreases soil erosion, and thus increases carbon storage potential in soil. The reduction will also make the soil more moist, which allows for greater carbon storage. Vegetation buffers, which are sections of land with specific vegetation, are purposefully designed to minimize water runoff, and thus soil erosion. Soil erosion leads to the loss of nutrients and carbon, so minimizing soil erosion decreases the amount of already stored CO_2 that the soil releases. Using a mulch tiller rather than the traditional fall plow reduces soil erosion by up to 40%. Planting crops perpendicularly to the slope decreases soil degradation because wind, among other weathering processes, is blocked. Snowfences and waterways are two other methods that hinder soil erosion.

The fourth agricultural option is good management of higher residue crops. While this also serves as erosion control, these crops (corn, grain, sorghum, and wheat) have cover that decreases soil density, which facilitates greater carbon absorption. The last agricultural option is winter cover crops, which like residue crops, have covers that serve to protect the soil underneath by minimizing weathering that leads to soil erosion.

Once all of the above agricultural options are implemented, the US soils have the capacity to store 380 mmt more than current soils can. From our research we found that the cost to the farmers for these changes is so small that it is negligible.

<u>Second sub-model: The Concept Green Freedom</u>

This sub-model assumes that cars and normal transportation motor engines can use synthetic gasoline as a source of fuel.

Green Freedom (GF) is a newly developed concept that consumes atmospheric CO_2 and converts it into gasoline and methanol. Although GF has not yet been implemented, its viability has been verified through in-depth research and reliable Los Alamos National Laboratory technical review. The process consists of two parts: methanol production and conversion of produced methanol into gasoline. The conversion part of the process uses the Mobil methanol-to-gasoline (MTG) technique. GF plants are more cost-efficient than previous plans of converting CO_2 into gasoline because this process incorporates breakthrough technology that extracts $CO_2$from the atmosphere more efficiently. 95% of the CO_2 that passes through the plant is captured within this more effective mechanism, as opposed to the 80% captured with less effective technologies. The energy needed to run the two parts of the process is obtained from nuclear power generated within the system. The energy production system accounts for over 50% of the cost of a GF plant.

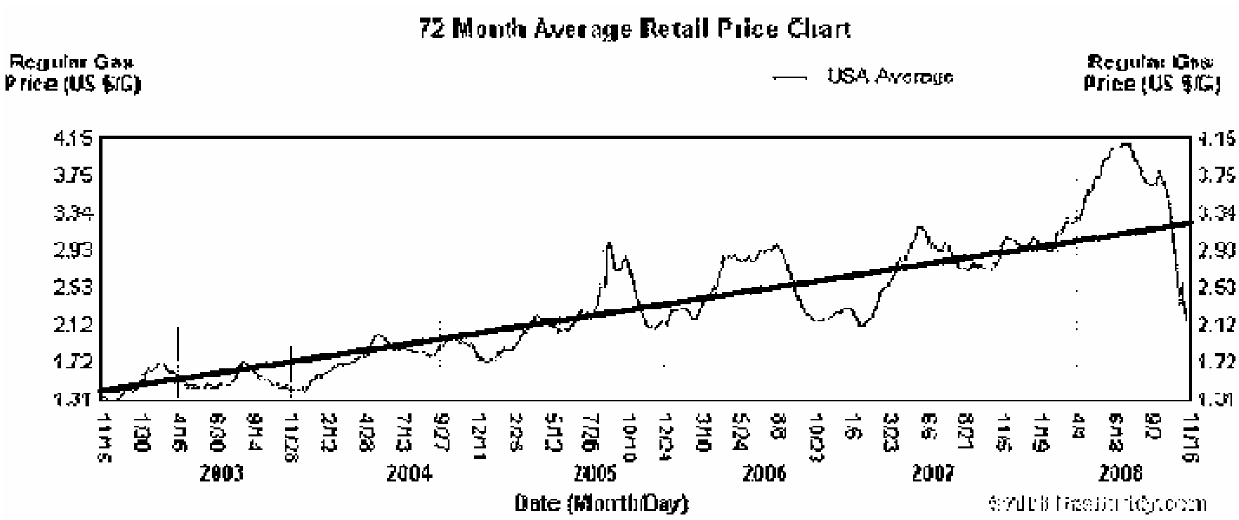
We determined the amount of atmospheric CO_2 consumed by the system per year. Since one GF plant produces 18,000 barrels (bbl) of synthetic gasoline per day, we could calculate the amount produced in a year: (18,000 barrels of synthetic gasoline/day)(365 days/year)(159 L/barrel)(0.75 kg/L)(1000 g/kg) = 7.835×10^{11} grams of synthetic gasoline is produced by one plant in one year. We converted grams into moles: (7.835×10^{11} g/year) x (1 mol / 114.23 g) = 6,858,728,005 moles of gasoline produced / year. We know that it takes 8 moles of CO_2 to produce 1 mole of gasoline (C_8H_{18} is the average molecular formula) since the gasoline's only source of the 8 carbons it needs per molecule is CO_2, so (6,858,728,005 mol C_8H_{18}) x (8 mol CO_2 / 1 mol C_8H_{18}) = 5.487 x 10^{10} mol atmospheric CO_2 consumed and converted into synthetic gasoline per year. Finally, we converted from moles into metric tons (MT): (5.487 x 10^{10} mol CO_2)(44 g/mol CO_2)(1 kg/1000 g)(1 MT / 1000 kg) = 2,414,272 MT atmospheric CO_2 consumed by one year of one Green Freedom plant. There are 847,400,000 metric tons of CO_2 left in the atmosphere after terrestrial sequestration methods are implemented. Thus, 847,400,000 MT of CO_2 / 2,414,272 MT CO_2 consumed by one GF plant in one year = 351 GF plants are needed to achieve atmospheric carbon neutrality.

Then, we determined the amount of profit we could make from selling synthesized gasoline. To do this, we had to figure out the cost of production of one gallon of synthesized gasoline. The rest of this paragraph is devoted to finding this cost. For the first part of the process, it takes \$.65 to process to produce one gallon (gal) of methanol. For the second part of the process, it takes \$1.40 to produce one gallon of synthesized gasoline from methanol. Thus, since we know that the methanol production part of the plant can produce 5,000 metric tons of methane per day (enough methane to convert into 18,000 barrels of gasoline), then the number of gallons of methanol produced per year is (5,000 MT methanol produced/day)(365 days/year)(1,000,000 g/MT)(1cm^3 / 0.795 g)(1 L / 1,000 cm^3)(0.2642 gallon / L) = 606,496,855 gal methanol / year. Thus, methanol production costs: (606,496,855 gal methanol / year)(\$.65 / gal methanol) = \$3.94222 x 10^8 / year = cost to produce methanol per year. Gasoline conversion costs: (18,000 bbl/day)(365 days/year)(42 gal/bbl)(\$1.4 / gal gasoline) = \$3.86316 x 10^8 / year = cost to convert methanol to gasoline per year. Adding the annual costs of methanol production and methanol conversion into gasoline, we found that (\$3.94222 x 10^8 + \$3.86316 x 10^8) = \$7.80538 x 10^8 = cost to run one GF plant for one year. Thus, the cost to run one plant for one day = (\$7.80538 x 10^8 / year)(1 year / 365 days) = \$2,138,460.274 / day. The plant makes 18,000 bbl of gasoline a day, which is (18,000 bbl/day)(42 gal/bbl) = 756,000 gal of gasoline made per day. Thus, it costs (\$2,138,460.274 / day) / (756,000 gal / day) = \$2.83 to produce one gallon of synthetic fuel.

We continue to find the profit that can be made from selling synthesized gasoline: currently, gasoline on the market costs \$3.20 per gallon, so our revenue would be \$3.20 per gallon sold. It costs the plant \$2.83 to make one gallon of gas. Thus, the profit the company makes per gallon of synthesized gasoline = \$3.20 (revenue) - \$2.83 (cost) + \$.37t (rate at which gas price increases per year) = \$.37 (revenue – cost) + \$.37t, where t = number of years after 2008. We found the rate of increase to be \$.37 per year by finding the slope of the line of best fit of the graph of year vs. price of gasoline per gallon. This can be seen in Graph 3 (see below).

We then turned the profit made from one gallon of synthesized gasoline into a function of time: p(t) = \$.37 + \$.37t. Then, we turned the function into the profit made in a year, by doing the following calculations: [(\$.37 + \$.37t)/gal](42 gal/bbl)(18,000 bbl/day)(365 days/year) = (\$.37+\$.37t)(\$275,940,000) / year= (\$102,097,800 + \$102,097,800t)/year = the profit made by the company per year. Please note that this function of profit does not take into consideration the initial capital cost.

Then, we anti-differentiated p(t) to find the new function P(t). P(t) = \$102,097,800t + \$51,048,900t^2 + C, where C is the constant. We then set the definite integral equal to initial cost, and let x = number of years needed for one GF plant to pay back its initial costs and the costs of running the plant for one year, so that it gets out of debt. Thus, the total profit from t=1 year to t= x years = $\int_1^x p(t)dt = P(x) - P(1)$ = (\$102,097,800x + \$51,048,900x^2 + C) – (\$102,097,800 + \$51,048,900 – C). Since the initial investment for building the plant is \$9.6 billion, we set that number equal to the total profit and solved for x: (\$9.6)(10^9) = (\$102,097,800x + \$51,048,900x^2 + C) – (\$102,097,800 + \$51,048,900 – C). After solving for x, we found that x = 12.7 years ≈ 13 years = approximate time it will take the plant to get out of debt.



Graph 3

Thus, the atmospheric emissions has been neutralized since (2,414,272 MT atmospheric CO_2 consumed by one year of one GF plant + 380 more mmt consumed by soil + 221,165,925 metric tons (mt) consumed by hard wood trees) = 603,580,197 mt of atmospheric CO_2 consumed by sub-models 1 and 2.1449 mmt CO_2 is emitted into the atmosphere, so our sub-models cannot neutralize atmospheric emission within the first year.

Then, we calculated the cost to operate one GF plant. We found that the initial capital to build one sequestering system is \$9.6 billion. For the first part of the process, it takes \$.65 to process to produce one gallon (gal) of methanol. For the second part of the process, it takes \$1.40 to convert one gallon of methanol into synthetic gasoline. Thus, since we know that the methanol production part of the plant can produce 5,000 metric tons of methane per day (enough methane to convert into 18,000 barrels of gasoline), then the number of gallons of methanol produced per year is (5,000 mt methanol produced/day)(365 days/year)(1,000,000 g/mt)(1cm^3 / 0.795 g)(1 L / 1,000 cm^3)(0.2642 gallon / L) = 606,496,855 gal methanol / year. Thus, methanol production costs: (606,496,855 gal methanol / year)(\$.65 / gal methanol) = \$3.94222 x 10^8 / year = cost to produce methanol per year. Gasoline conversion costs: (18,000 bbl/day)(365 days/year)(42 gal/bbl)(\$1.4 / gal gasoline) = \$3.86316 x 10^8 / year = cost to convert methanol to gasoline per year. Adding the annual costs of methanol production and methanol conversion into gasoline, we found that (\$3.94222 x 10^8 + \$3.86316 x 10^8) = \$7.80538 x 10^8 = cost to maintain and run one GF plant. Finally, \$7.80538 x 10^8 + \$9.6 billion (initial capital to build the plant) = amount of money the GF plant needs to borrow from the government. The company will then pay the government back eventually with its annual profit.

For our sub-model, \$9.6 x 10^{10} is invested to construct ten GF plants. Profit from ten initial plants is then invested to construct a new GF plant whenever the sum of the profit is large enough. For example, the first new GF plant after the original ten can be constructed in 2012 because $\int_1^4 f(t)dt >$ \$9.6 x 10^{10}, the amount of money needed for the construction of a GF plant, and it's the soonest that this happens.

Third sub-model: Building algae-based biodiesel factories

There were a few assumptions that we made for this sub-model. First, all biodiesel created can, and will be sold at the current average market price. This maximizes the revenue. Second, the energy provided by the excess heat from the other activities of the power plant is enough to supply the basic algae mechanisms with energy and thus the annual operating cost is negligible.

While all plants consume CO_2, they unfortunately release all the CO_2 again once they die. However, these plants can be used to produce biofuel before they die and emit the additional CO_2. The produced biofuels, in turn, are neutral in terms of emission of CO_2 because the amount of CO_2 released when burning them is balanced by the CO_2 absorbed during the production of the biofuel through the biomass. This is much more advantageous than petroleum, which does not absorb CO_2 despite its heavy emission.

Algae have been found to be the most efficient in producing biofuels; an acre of algae ponds produces up to 15,000 gallons of biodiesel and 25,000 gallons ethanol per year. Algae also consume the most amount of CO_2 per year, compared to other plants used for biodiesel production, such as corn, palm, soybeans, or rapeseeds. Thus, we chose to use algae as the plant that will consume CO_2 produced by the power plant and be converted into biofuels.

There are approximately 1000 power plants in the US that have enough space that is close enough to the power plant to build algae ponds. Those 1000 power plants have, on average, 1500 unused acres to grow an algae farm. Thus, (1000 power plants)(1500 unused acres / power plant) = 1,500,000 acres to grow algae farms. An acre of algae farm consumes approximately 202.35 metric tons of CO_2 per year, so (1,500,000 acres)(202.35 mt / acre) = 303,525,000 mt of CO_2 consumed per year by soon to be built algae farms.

Each power plant in the country emits, on average, 2.8 billion tons of CO_2. (2.8 billion tons)(.9072 mt / ton) = 2540 mmt available to be used for algae based biofuel plants. Since there are 1.5 million acres of newly built algae ponds, and it costs \$40,000 to build one hectare of an algae pond, (1.5 million acres)(.4047 hectares / 1 acre)(\$40,000 / hectare) = \$2.428 x 10^{12} = the cost to build 1.5 million acres of algae plant. The government will loan this money to power plants; the power plants will eventually pay the government back through the money earned through selling the biofuel the algae plants produce. After the power plant pays the government back, it can keep the money it makes from the algae plants. Therefore, building algae plants both consumes CO_2, thus helping the environment, and serves as a long term investment for power plants and the government.

One acre of algae pond can yield 15,000 gallons of biodiesel, so (1.5 million acre)(15,000 gallons biodiesel / acre) = 2.25 x 10^{10} gallons of biodiesel produced per year. It costs \$.59 to convert one gallon of algae to biodiesel, so (2.25 x 10^{10} gallons of biodiesel)(\$.59 / gallon) = \$1.3275 x 10^{10} = the cost, per year, to produce the biodiesel. Currently, one gallon of biodiesel can be sold for \$1.85, so (2.25 x 10^{10} gallons of biodiesel)(\$1.85 / gallon) = \$4.1625 x 10^{10} = the amount of money earned per year from selling biodiesel produced on the algae plants. Thus, (\$4.1625 x 10^{10} – \$1.3275 x 10^{10}) = \$2.835 x 10^{10} = the profit a power plant can earn through biodiesel produced from algae plants. This calculation can be similarly applied to the ethanol produced from algae farms. (1.5 million acres)(25,000 gallons ethanol produced / 1 acre) = 3.75 x 10^{10} gallons ethanol. (3.75 x 10^{10} gallons ethanol)(\$1.50 / gallon ethanol) = \$5.625 x 10^{10} = the cost to convert algae to ethanol. (3.75 x 10^{10} gallons ethanol)(\$2.62 / gallon ethanol) = \$9.825 x 10^{10} = revenue from selling the produced ethanol. Thus, (\$9.825 x 10^{10} – \$5.625 x 10^{10}) = \$4.200 x 10^{10} = the profit a power plant can earn through ethanol produced from algae plants. Thus, the grand profit = \$2.835 x 10^{10} (revenue from biodiesel) + \$4.200 x 10^{10} (revenue from ethanol) = \$7.035 x 10^{10} per year. Hence, \$2.428 x 10^{12} (the cost to build 1.5 million acres of algae plant) / \$7.035 x 10^{10} (revenue made from the algae plants per year) = 34.513 = approximate years it will take for the power company to pay the government back.

<u>Fourth sub-model: Carbon Capture and Storage (CCS) into geologic formations</u>

Our fourth sub-model involves two different types of CSS: CO_2/EOR (Enhanced Oil Recovery) and Enhanced Coalbed Methane Recovery (ECMR). Both types involve injecting CO_2 into underground geological formations.

There were two assumptions made for this sub-model. First, all remaining coal present in the coal seams is of the correct composition for ECMR and that all are within a feasible proximity to a power plant. Second, all methane and oil produced can, and will be sold at the current average market price. This maximizes the revenue.

For our first type of CCS, CO_2/EOR, CO_2 is injected into oil reservoirs that have already gone through primary and secondary recovery. Primary recovery consists of directly pumping the oil up (this is possible due to already existent pressure in the reservoir), and secondary recovery consists of injecting an external fluid into the reservoir that displaces the oil, thus creates pressure, and pushes the oil up and out of the reservoir. In these oil reservoirs, there is still a significant amount of remaining oil that cannot be tapped relying on solely primary and secondary recovery methods. EOR, also known as tertiary recovery, specifically uses CO_2 as a means of creating the necessary conditions to tap the remaining oil is referred to as CO_2/EOR. Once CO_2 gas is injected into the chamber, it mixes with the remaining oil, expands the oil, increases its viscosity, and thus allows it to flow to the production well. It takes approximately 8,000 cubic feet of CO_2 to bring up one barrel of oil. We then converted this number to metric tons, under the assumption that the CO_2 gas is at Standard Temperature and Pressure (STP). STP allows for conversion ease, but is also moderately realistic given the situation. Since there are 28.3 liters in 1 cubic foot, (8,000 ft^3 CO_2)(28.3 L / 1 ft^3) = 226,400 L CO_2. The density of CO_2

gas is 1.98 g/L at STP, so (226,400 L CO_2)(1.98 g/L) = 448,272 g = 448.272 kg = 0.448 metric tons (mt) = the amount of CO_2 needed to inject into oil reservoirs to bring up one barrel of previously irremovable oil.

Next, we found that the US Department of Energy says that a total of 240 billion barrels of stranded oil can be recovered through EOR. We then calculated the total possible CO_2 consumption through EOR: (240 billion barrels of oil)(0.448 mt CO_2 / barrel of oil) = 107.5853 billion metric ton (bmt) can be consumed, over time assuming barrels of oil are obtained. The large scale of this number will be addressed later.

Overall EOR profit = \$3.563 x 10^{12}.

The second type of CCS, Enhanced Coalbed Methane Recovery, uses pipelines from abandoned or unmineable coal seams to sequester carbon dioxide and increase methane production. In this method, carbon dioxide is pumped from power plants into the mines using equally spaced wells and displaces the methane present in the coal already. The methane is then collected and sold. The CO_2 that is injected into the coal is converted to carbonate within the coal and permanently stored. We assumed that all unmineable coal seams can be mined with ECMR.

We found that there are 1,000 total underground mines, 10% of which are abandoned or unmineable. Thus, there are 100 mines available for ECMR. We also found that the average consumption of CO_2 per mine is 15 bmt so (100 mines)(15 bmt CO_2 consumed / mine) = 1500 bmt of CO_2 consumed through all possible ECMR. The large scale of this number will be addressed later.

We found that it costs \$40 to consume a ton of CO_2 through ECMR. Thus, the cost of all 1500 bmt is (1500 bmt CO_2)(\$40 / ton CO_2) = \$6 x 10^{13} = cost to mine all the remaining coal through ECMR.

We also calculated the amount of money brought in from methane sales. Studies show that coal can hold approximately twice as much CO_2 as methane, so (1500 bmt CO_2)(1 part methane / 2 parts CO_2) = 750 bmt of methane. The retail price of methane is \$6.39 per 1,000 ft^3 methane, so if all methane is sold at the market price, the total revenue of methane sales = (\$6.39/1000 ft^3 methane)(35.311 ft^3/m^3)(1 m^3/.717kg methane)(1000kg/mt)(1,000,000,000 mt/bmt)(750bmt) = \$2.360 x 10^14. Thus, total profit from ECMR = (\$2.360 x 10^{14}) – (\$6 x 10^{13})= \$1.76 x 10^{14}.

Our calculations show that ECMR is an effective long term method of carbon sequestration because it ultimately pays for itself. However, this is extremely difficult to incorporate into our yearly model because these numbers account for the CO_2 consumption of *all* coal seams that can be mined through ECMR. Recovery of coal seams through ECMR is not a renewable carbon dioxide sequestration method because once they have been filled with CO_2, no more can ever be added. In other words, if we mined all the coal seams in one year, we would be consuming much more CO_2 than is available. Therefore this CO_2 consumption and profit would occur over a span of time.

Since we found that our third algae plants sub-model will consume 303,525,000 mt of carbon dioxide from power plant emission per year, our fourth CCS model must consume (2540 million metric tons of CO_2 emitted total by power plants – 303,525,000 mt of power plant CO_2 consumed) = 2236.5 mmt of CO_2 that must be consumed by CCS (both EOR and ECMR). With this information, we found the ratio of EOR and ECMR to the total CO_2 consumption, then applied those ratios to the necessary yearly consumption. We found these ratios to ensure that the EOR and ECMR would stop consuming CO_2 at the same time.

Maximum CO_2 consumed by both EOR and ECMR is (107.64936 bmt CO_2 consumed through EOR + 1500 bmt of CO_2 consumed through ECMR) = 1607.646 bmt. The ratio of CO_2 consumed through EOR to the total CO_2 consumed through CCS = 107.646 bmt/1607.646 bmt = .06696. The ratio of CO_2 consumed through ECMR to the total CO_2 consumed through CCS = 1500 bmt/1607.646 bmt = .93304. We found earlier that 2236.5 mmt of power plant emitted CO_2 must be consumed by CCS per year. So, out of that annual amount, EOR will consume (2236.5 mmt)(.0669) = 149.756 mmt/year and ECMR will consume (2236.5 mmt)(.93304) = 2086.744 mmt/year. Thus, the emitted carbon from power plants has been neutralized since 149.756 mmt (CO_2 consumed by EOR) + 2086.744 mmt (CO_2 consumed by ECMR) + 303,525,000 mt (CO_2 consumed by algae biodiesel plants) = 2542 mmt CO_2 consumed ≈ amount of CO_2 emitted by factory plants (2540 mmt CO_2).

Thus, even though CCS is a limited method that cannot be relied upon forever because the oil reserves and coalbeds that the CO_2 is being injected into will eventually run out, it will take many years until that occurs (given we only employ CCS as much as is necessary to neutralize the carbon emissions by power plants). The number of years we can apply EOR is (107.646 bmt CO_2 consumed through EOR)(1000 mmt/bmt) / (149.756 mmt consumed through EOR/year) = 718.81 years. As expected from our calculations, the numbers of years we can apply ECMR should be the same: (1500 bmt CO_2 consumed through ECMR)(1000 mmt/bmt) / (2086.744 mmt consumed through ECMR/year) = 718.81 years. Therefore, the combination of EOR and ECMR (CCS) can continue to fill the need for CO_2 consumption to maintain neutrality of power plant emissions for 718.81 years. It is safe to assume that by that time, new CO_2 sequestration methods and alternative fuels will have been developed so that CCS no longer has to be relied upon.

V. ECONOMIC SUMMARY AND ANALYSIS

Each sub-model has a set of economic specifications contributing to the larger economic impact of our entire model. For all models we assume that it takes one year to get the technology in place, thus the costs of acquiring the technology will not extended for subsequent years. The conditions for each sub-model are as follows:

1. *Terrestrial sequestration: planting trees and land/soil management* – Planting trees has one flat rate for the first year of program implementation. Because the trees that we chose are extremely low maintenance we assume that there is no annual cost after the first year of program implementation. The initial cost of this sub model is $2,031,841,294. There is no economic profit associated with this model. Land management involves basic changes to farming behavior that have minimal economic consequences for both the farmer and the government. We recognize that the rotation of crops could be an additional burden for

farmers, but this would likely be offset by the time that is no longer spent tilling the fields. Tax benefits and subsidizes could be taken into account, but we chose not to address them in this model. Therefore, there is not economic impact from this particular model.

2. *Green Freedom Technology:* The profits of the Green Freedom technology is based entirely on the rising prices of gas in the United States. As gas prices increases the profits of the plants increases, as the profits of the plants increase the money is put back into the system to build more plants until we reach the point, 351 plants, when carbon neutrality can be reached. There is a substantial start up price, \$9.6 x 1010, per plant that must be raised and put in to start each new plant, thus slowing the process.

3. *Algae-based Biodiesel Factories*: In this model, the government offers the 1,000 factories that have the space to add algae fields and conversion mechanisms the money to establish this new technology. As the companies sell the biodiesel made from algae oil, the profit from those sales (\$7.035 x 10^{10}) will go towards paying down their government loan. Once they complete their payments, after 34.5 years, the profit will go to the company. This means that this is a long term investment for both the government and the power company. Eventually, the algae fields will be economically beneficial even though the establishment price, \$2.428 x 10^{12}, may seem daunting. We assume that the energy provided by the excess heat from the other activities of the power plant is enough to supply the basic algae mechanisms with energy and thus the annual operating cost is negligible.

4. *Carbon Capture and Storage (EOR and ERCM)*: This sub model essentially pays for itself after the first year of consumption as the profits from methane and oil are greater than the operation costs of EOR and ERCM. The total money movement follows:

Annual Costs:
- EOR: \$2.8433 x 10^8
- ERCM: \$83,469,760
- Total: \$367,799,760

Annual Revenue:
- EOR: \$3.338 x 10^8
- ERCM: \$3.283 x 10^{11}
- Total: \$3.286 x 10^{11}

Annual Profit
- EOR: \$4.957 x 10^7
- ERCM: \$3.282 x 10^{11}
- Total: \$3.282 x 10^{11}

As there is little that needs to be done to establish the technology, the annual costs are equivalent to the costs of the first year of operation.

Also, please note that the first sub-model (terrestrial sequestration) has been divided into two different sub-models in these charts because they have different expenses.

Sub-Model	First year expenses of programs
1. Planting Trees (Terrestrial Sequestration)	$2,031,841,294
2. Land Management (Terrestrial Sequestration)	$0
3. Algae-based Biodiesel Factories	$2,428,000,000,000
4. Carbon Capture and Storage (CCS)	$367,799,760
5. Green Freedom Technology	$ 96,000,000,000
Total:	$2,526,000,000,000

Sub-Model	Annual Cost (after the first year, not including start costs)
1. Planting Trees (Terrestrial Sequestration)	$0
2. Land Management (Terrestrial Sequestration)	$0
3. Algae-based Biodiesel Factories	$0
4. Carbon Capture and Storage (CCS)	$367,799,760
5. Green Freedom Technology	$780,540,000 (for the first 1-3 years, this increases as investment in power plants increases)
Total:	$1,148,339,760

Sub-Model	Annual Revenue
1. Planting Trees (Terrestrial Sequestration)	$0
2. Land Management (Terrestrial Sequestration)	$0
3. Algae-based Biodiesel Factories	$70,350,000,000 – This money will go to the government until the debt has been paid off (34.5 years after establishment)
4. Carbon Capture and Storage (CCS)	$3.286x10^{11}$
5. Green Freedom Technology	Changes because revenue is proportional to the changing prices of gasoline
Total:	$3.989 x 10^{11}$

Sub-Model	Net Spending for First Year of Program (= revenue – cost)
1. Planting Trees (Terrestrial Sequestration)	- $2,031,841,294
2. Land Management (Terrestrial Sequestration)	$0
3. Algae-based Biodiesel Factories	- $2,357,650,000,000
4. Carbon Capture and Storage (CCS)	+ $3.282 x 10^{11}$
5. Green Freedom Technology	- $1.0125 x 10^{11}$
Total:	- $2,132,880,000,000

Sub-Model	Annual Net Spending (after first year)
1. Planting Trees (Terrestrial Sequestration)	$0
2. Land Management (Terrestrial Sequestration)	$0
	There is no annual operation fee for

3. Algae-based Biodiesel Factories	the plant, however the profits are being given back to the government to repay the debt. + $70,350,000
4. Carbon Capture and Storage (CCS)	$\$3.282 \times 10^{11}$
5. Green Freedom Technology	Changes yearly with profit changes
Total:	$\$3.282 \times 10^{11}$

Current annual budget for environmental spending: $60,590,000,000

With all sub-models in action at the same time:

1st year net spending = -2.1338×10^{12}

Debt : $-\$2.0722 \times 10^{12}$

Obviously, this debt makes our full scale model grossly unrealistic. Because our largest money sinks and most unstable numbers come from the new technology, algae factories and Green Freedom Technology, we decided to eliminate those two sub-models to create a more feasible model. This model that includes all of the sub-models is the most environmentally successful, but far too idealized to be economically feasible.

New model net spending: $+\$3{,}261 \times 10^{11}$

Without the new technology we not only help the environment, but we contribute to the amount of money set aside for additional environmental initiatives. Once that surplus grows large enough, we can begin to invest in more innovative technology such as algae and Green Freedom Technology.

VI. SOCIAL IMPACT

Social impact statement: While these changes do not introduce a paradigm shift or any other large scale impact, they do have an influence on the lives of a select group of people. For example, farmers are being forced to make changes to their crops, crop rotations and farming practices which could disrupt their business and daily life. All Americans are being asked to plant trees, which, for some, could be a burden. However, the over all impact of these changes outweighs the slight personal burdens that may ensue. Therefore, this model is socially feasible.

VII. CONCLUSIONS

The total amount of carbon dioxide consumed by our all four of our sub-models, is 3165333645 mt. This is shown in the following table.

Sub-Model	Carbon Dioxide Consumed per Year (mt)
1. Planting Trees (Terrestrial Sequestration)	221,165,925 mt
2. Land Management (Terrestrial Sequestration)	380,000,000 mt
3. Algae-based Biodiesel Factories	303,525,000 mt
4. Carbon Capture and Storage (CCS)	2,236,500,000 mt
5. Green Freedom Technology	>24142720 mt – this will increase over time
Total:	3165333645 mt

In our idealized model, and assuming that the Green Freedom Technology increases its consumption as expected, we can reach carbon neutrality for both power plant and atmospheric emissions in 35 years.

For our model that is economically feasible, it is possible to reach carbon neutrality in power plant emissions by expanding the amount of CCS employed in carbon sequestration per year. Thus, 2540 mmt/3989 mmt, or 63% of all CO_2 emissions will be consumed using only CCS. Without Green Freedom Technology it is not possible to reach neutrality for atmospheric emissions. With the terrestrial sub-models alone (tree planting and land management practices) 601.165/1449, or 41.49% of atmospheric emissions will be consumed. Overall, with out algae and Green Freedom Technology, %78.75 of all human CO_2 emissions will be consumed. Eventually neutrality will be reached as the new forms of technology are added based on budget capabilities.

VIII. STRENGTHS OF THE MODEL

First Sub-model: terrestrial sequestration

- Minimal social impact results from this sub-model.
- Helps farmers by making the land healthier and more beautiful.
- The sub-model does not cost farmers additional money or energy.
- The sub-model utilizes unused space.

Second Sub-model: Green Freedom Technology

- This sub-model achieves a significant amount of atmospheric CO_2.
- The system itself is completely carbon neutral.
- Allows the US to become less dependent on fossil fuels and foreign fuels.

Third Sub-model: building algae-based biodiesel factories

- The technology is efficient.
- The sub-model uses space that could likely not be used for anything else.
- There is no social or cultural impact.

Fourth Sub-model: CCS

- This sub-model is a very controlled method because it is based on how much CO_2 we still need to consume.
- Utilizes safe and permanent means of storage.
- Pays for itself.

Overall model

- If given the sufficient loans, the implementation of all of our four sub-models are able to completely neutralize total CO_2 emissions.

IX. WEAKNESSES OF THE MODEL

First Sub-model: terrestrial sequestration

- Even by assumptions it is unrealistic that all trees would be planted.
- We do not take into account the CO_2 emitted when the hardwood trees die.
- We do not consider the effect on the balance of the ecosystem when a surplus of hardwood trees is added.

Second Sub-model: Green Freedom Technology

- New technology is introduced, so unforeseen problems may arise.
- Requires the Green Freedom plants and government to make long-term investments. With current economic conditions, many may be unwilling to make the commitment.

Third Sub-model: building algae-based biodiesel factories

- New technology is introduced, so unforeseen problems may arise.
- Requires power plants and the government to make long-term investments. With current economic conditions, many may be unwilling to make the commitment.

Fourth Sub-model: CCS

- There is a limited amount of reservoirs and coalbeds that can be used to store CO_2.
- Assumes hat all unmineable areas can be used for ECMR, but that is likely not the case.
- Assumes that all 240 billion barrels of oil are retrievable.
- The cost does not take into consideration the transportation costs of CO_2 from the power plant to the reservoirs/coalbeds.
- Other costs not taken into account.

Overall model

- Most likely, the government will not be willing to loan all the money needed to implement all sub-models.

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