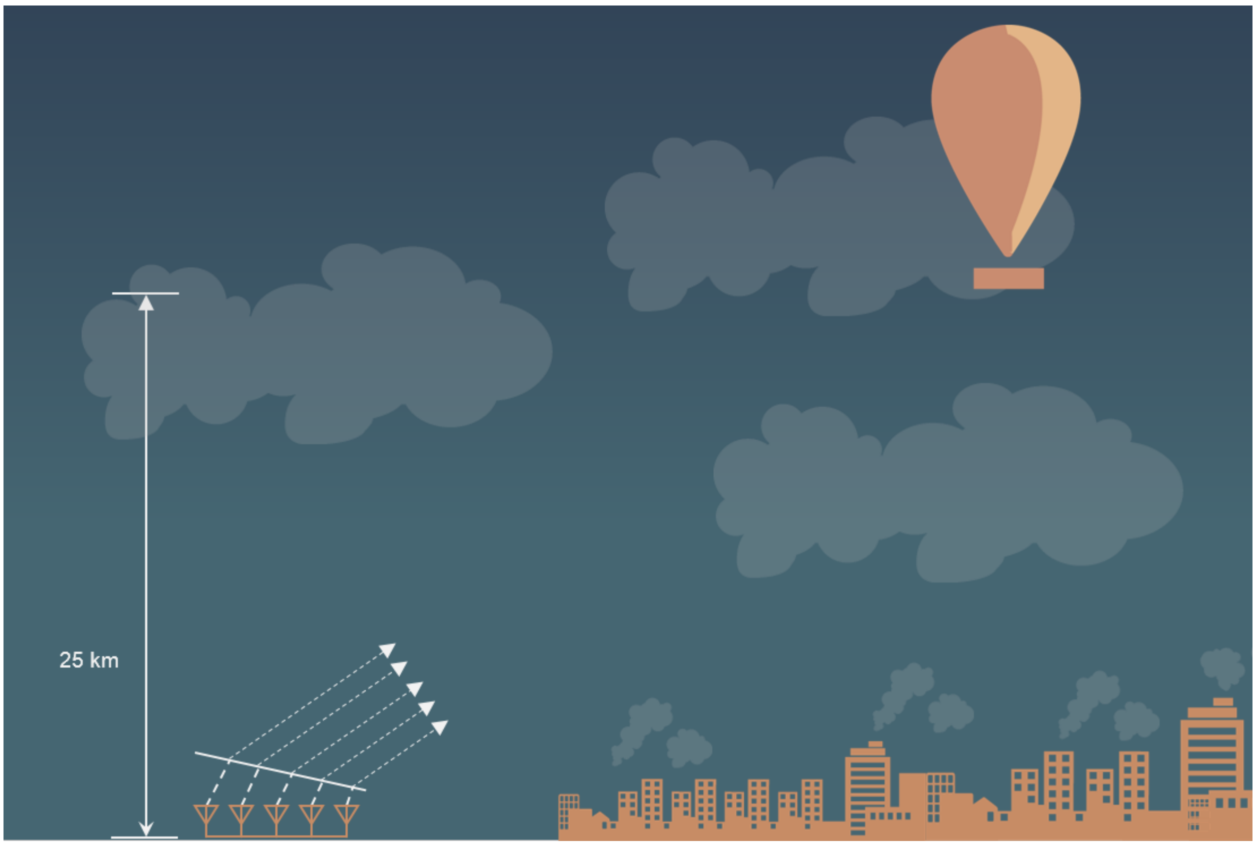
ENGINEERING SOCIETY 4Y03

FINAL REPORT

GROUP HIGH ALTITUDE BALLOON



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Introduction

It is well know that climate change is a growing global concern. Government and private interests in combatting climate change have been increasing over the last few decades. A method of abating the adverse effects is scrubbing greenhouse gasses out of the atmosphere. Greenhouse gases act as a “heat sink” that prevents UV heat from escaping from the planet into space, resulting in changes in global temperatures and weather patterns. According to several reports, if we stop emitting any CO_2 immediately, the CO_2 released into the atmosphere by humans will stay in the atmosphere for hundreds, if not thousands of years before being totally absorbed back by the planet [1][2].

This project looks at the possibility of reducing pollutants and greenhouse gases at a high altitude (~25 km), in order to combat climate change. This will be done via literature review of existing gas capturing and disposal methods. It is found that carbon dioxide is the most concerning greenhouse gas presently, and that planting trees is not an efficient method for carbon capture. Additionally, current alternative carbon capture and storage (CCS) technologies are discussed. The main purpose for this report is the in depth outline of MEA and cryogenic carbon capture methods at 25 km altitude. Two different approaches to each of these technologies are described and compared in terms of cost, mass, energy and associated resonance time of the high altitude balloon.

An analysis of stakeholders and background information is explored in the Appendices.

Table of Contents

Introduction 2

Table of Contents 3

Which Greenhouse Gas is Most Concerning?................................. 4

Scrubbing on Ground..4

Amine Carbon Capture...7

Industrial Process...8

Microchannel Reactor..14

Cryogenic

Liquefaction..17

Public Relations...21

Conclusion 23

References 24

Appendix A 29

Appendix B..32

Which Greenhouse Gas is most concerning?

Research was performed to gather background information about current atmospheric concentrations of different GHGs. In short, we found out that CO_2 is by far the greenhouse that is most responsible for climate change; and is indeed the one we should be targeting. Although there are other “more damaging” greenhouse gases per particle in the atmosphere, scrubbing any of it will not yield any effective results in fighting climate change due to their relatively negligible amount that exists in the atmosphere. Thus, carbon dioxide is the greenhouse gas to target (Appendix B).

Scrubbing on Ground

As a basis for comparison later on, we need to compare our research of scrubbing greenhouse gases at a high altitude to doing a similar procedure on the ground. Currently, there are both the natural and the technological ways of doing so - although the latter is mostly in stages of research and development and has yet to be commercialized.

Trees

Although trees do help, they were not purposely designed to solve this specific man-made problem, and thus cannot be fully relied on to solve the problem of climate change. This is because trees tend to have a couple of very unique characteristics which limit it in terms of combating climate change - especially long term.

The first of those characteristics is the fact that trees tend to “breathe out” up to half of the carbon dioxide that they absorb on a daily basis [3]. This happens as a result of burning down the sugar that they initially create from photosynthesis, in order to feed themselves. Moreover, like any living organism, trees eventually die which typically tends to be anywhere from 20 to 50 years [5]. The problem - in this case - is that once that happens, the tree releases all of the carbon dioxide that it has absorbed from the environment over its lifetime [2][3]. Lastly, many scientists believe we can build “artificial trees”, or simply CO_2 scrubbers, that are far more efficient in terms of the rate at which they can scrub and the space they need [4]. Thus, as long as climate change is concerned, although trees help relieve the problem, they are not an effective the solution to the problem.

Trees will still be used as a reference to rank the other methods that are discussed in this paper. For the purpose of this project, the group followed a method of calculating and estimating the average amount of CO_2 absorbed by a tree - done by Environmental Monitoring and Community Resilience Division, at the Broward County of Florida - and the average amount was 50 pounds per tree per year [5]. This number varies based on many variables, like the tree type, its age, environment, etc. However, this average number will be used as our reference when comparing trees to other methods.

Other technologies

Besides trees, there are a number of other technologies that have been or are being developed that are designed to capture greenhouse gases. Most of these technologies are either secretive due to the nature of the application they are used in - like scrubbing greenhouse gases used by NASA [6] in their space shuttles, or similar technologies used inside submarines [7] - and most of the other ones are still in early stages of research and development. Out of those technologies, the following are outlined below;

- A Canadian start-up company, called *Carbon Engineering*, has been developing a technology that allows it to capture air, then mix it with a “capture solution” that scrubs the CO_2 out of the air, all in a modular design that can be built anywhere on the ground [8] (Figure 1). The company is led by David Keith, a University of Calgary professor, and financially backed by Bill Gates [9]. Once captured, one of the ways the carbon dioxide can be used, is by mixing it with hydrogen to convert it to liquid hydrocarbons - to be able to use it as fuel for existing jets and cars alike. This has another dimension of benefits to it, as it would mean we do not need new electric infrastructure for electric cars and such, emitting the costs and emission from building such infrastructure [10].

- Another research is looking into electrolytic conversion of CO_2 captured from the atmosphere into Carbon Nanofibers or CNFs, by dissolving it in molten carbonates. The yielded product would then be used as a strong building material making the whole process very sustainable [11].
- Another company, called *Global Research Technologi*es, is trying to commercialize technology that captures CO_2 through solid sheets coated with a sorbent that trap the CO_2 (Figure 2). The technology is estimated to potentially capturing one tonne of CO_2 a day from a machine the size of a standard shipping container [6]. The company believes that it can sell the captured CO_2 to be used in greenhouses to improve plant yields, food processing, water treatment, fire extinguishers, as well as oil fields where the captured CO_2 can also be used to increase the amount of oil recovered from those fields.
- *Global Thermostat*, named among the world's ten most innovative energy companies, is using an already proven method of capturing CO_2 using amines - a method that is in use to capture concentrated CO_2 emitted from fossil-fuel power plants. There is a more in depth discussion later in the document [12].
- Lastly, a group of scientists from USC's Lokar Hydrocarbon Research Institute have come up with a new plastic material that captures CO_2 from the air using a polyamine based re-generable solid adsorbent [13]. They were able to produce a type of plastic that can simply trap the carbon dioxide molecules at room temperature. The material itself consists of an organic compound called polyethylenimine (PEI) which has been coated onto grains of silica [7]. According to the team, the material is lightweight, cheap to produce, and works very well at room temperature.

Figure 1 - Carbon Engineering's Technology [8]

Figure 2 - GRT's Technology [6]

Amine Carbon Capture

Amines are organic compounds that contain a nitrogen atom and a lone pair. A subgroup of these, belonging to the primary amine family, react readily with carbon dioxide and hydrogen disulfide and are used in industry to remove these unwanted greenhouse gases. The prominent chemicals of this amine family include monoethanolamine (MEA), diethanolamine (DEA) and diglycolamine (DGA). These chemicals are produced and normally purchased in industrial quantities.

	Cost ($CAD/kg)	Heat of Reaction (kJ/kg)	Rate of Reaction (m^3 $kmol^{-1}$ s^{-1})
Monoethanolamine	1.6-1.8	1919	5545
Diethanolamine	1.5-2.5	1519	2375
Diglycolamine	5	1977	4517

Table1: Cost and Physicochemical Properties of Select Amine Compounds [20]

Due to the nature of these compounds, they require slightly different concentrations in their liquid solution for optimum carbon capture. According to Warudkar et al, these are as follows: MEA 20 wt%, DEA 40 wt% and DGA 60 wt%. Therefore it can be assumed that, by weight, MEA is favourable in terms of efficient material usage. It has been found that most simulations of MEA in literature is run at 30 wt% [17]. This will be used for this conceptual design.

For the purpose of this literature review, the main focus will be on MEA due to its relatively low cost and high reaction rate. Additionally, it has ostensibly the most researchable information and published testing data, as it is the standard chemical absorbent used in flue gas carbon capture.

Industrial Plant MEA

The ubiquitous form of industrial carbon capture happens post-combustion and pre-emission into the atmosphere. The flue gas is fed through the MEA setup shown and removes gases. The process typically removes 85-90% of the carbon dioxide.

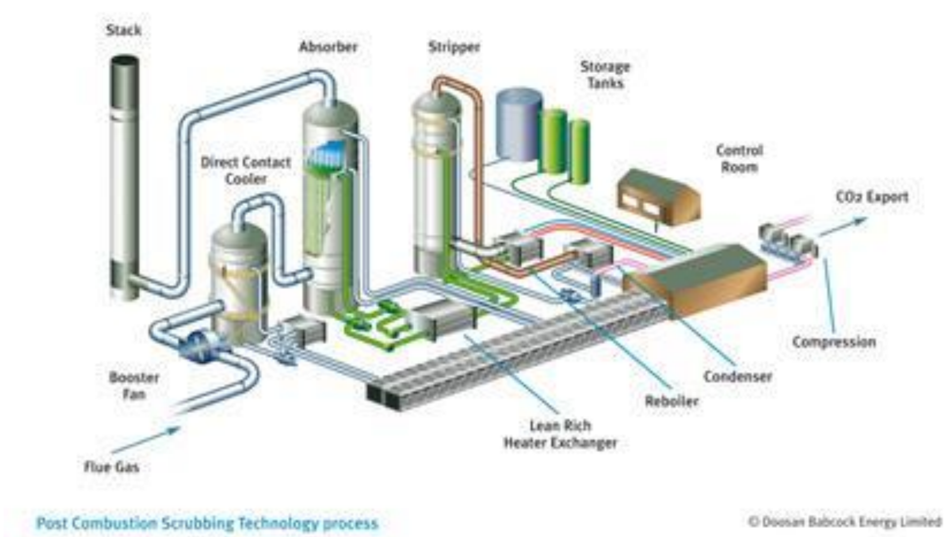


Figure 3: Typical Industrial MEA Carbon Capture Setup [14]

Process

In a typical amine carbon capture process as shown, the flue gas is pumped towards the absorber by virtue of a blower. In the absorber, the CO_2 and other greenhouse gases react with the amine solvent. The purified air is pumped back out to the chimney stack while the CO_2-rich amine solution is pumped into a heat exchanger. The heat exchanger increases the temperature of the rich amine in preparation for entering the stripper. At this point, the CO_2-lean solution is pumped back into the top of the absorber to react further. This refeed enters the absorber at 45∘C. The rich solution enters the stripper at 110∘C. In the stripper, steam at 415 kPa is pumped into the chamber to separate the amine from the carbon dioxide. The ideal stripper pressure in terms of efficiency when using MEA is 300 kPa. At this pressure and temperature, the CO_2 and steam can be pumped out through the top of the stripper, with the used amine being either pumped out for storage or back towards the absorber. The moist CO_2 passes through a condenser, and the water vapour is left behind while the carbon dioxide is compressed for storage [20].

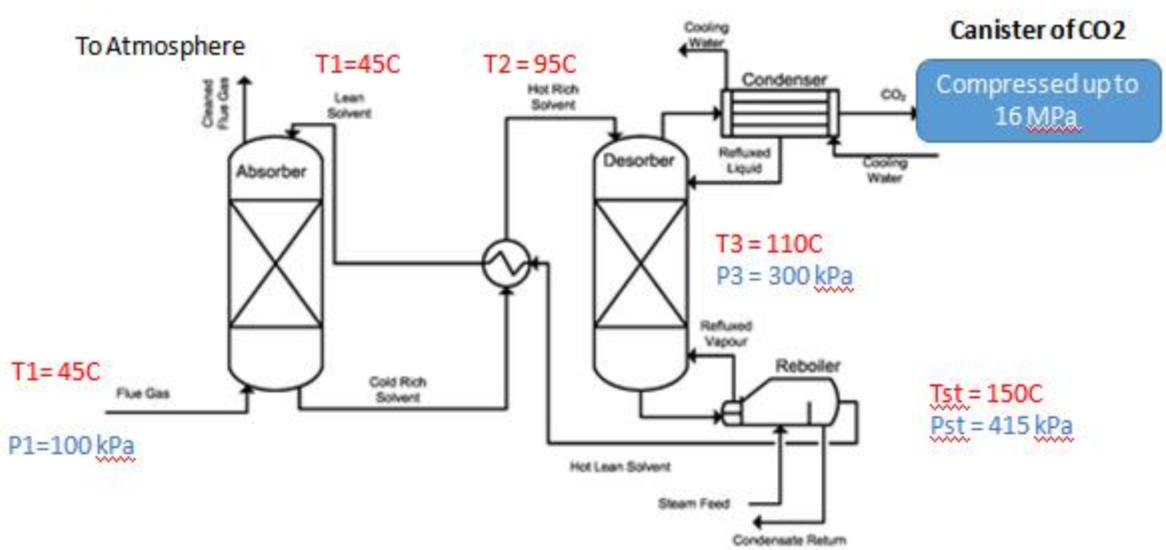


Figure 4: Ideal MEA Carbon Capture Process with Stage Characteristics

Constraints

As an initial constraint to carbon capture, note that the absorber should not contain more than 0.4 mol CO_2/ mol amine. Beyond this value, the reaction rate drops off, making the typical industrial design inefficient. Within the scope of the High Altitude Balloon, requiring a lower CO_2 weighting should not be a limiting factor, as atmospheric concentrations are far lower than those studied in industrial processes (0.04% to 40%). What this implies is that a higher mass flow rate blower should be used to accommodate for the low concentration.

Power

In a 400 MW coal-fired power plant the low pressure turbines provide 45% of the power. The reboiler in the stripper in the MEA carbon capture process requires the steam from these turbines and leech up to 40% of the power plant's output. According to Warudkar et al, in ideal conditions with the 300 kPa stripper pressure this still results in a 38.6% parasitic power loss using MEA [20] For this project, a similar setup is simulated with numbers scaled down from a 500 MW power plant to a 500 kW power input to the steam reboiler, heat exchangers and pumps. This assumes the balloon will be receiving 500 kW power exclusively for this MEA process (analogous to 'parasitic power')[19].

High Altitude Process and Design

Significant considerations need to be made for capturing carbon using monoethanolamine at the conditions specified in the High Altitude Balloon project. At 25 km altitude, the atmospheric pressure and temperature is 0.1 atm and -51.5 C, respectively.

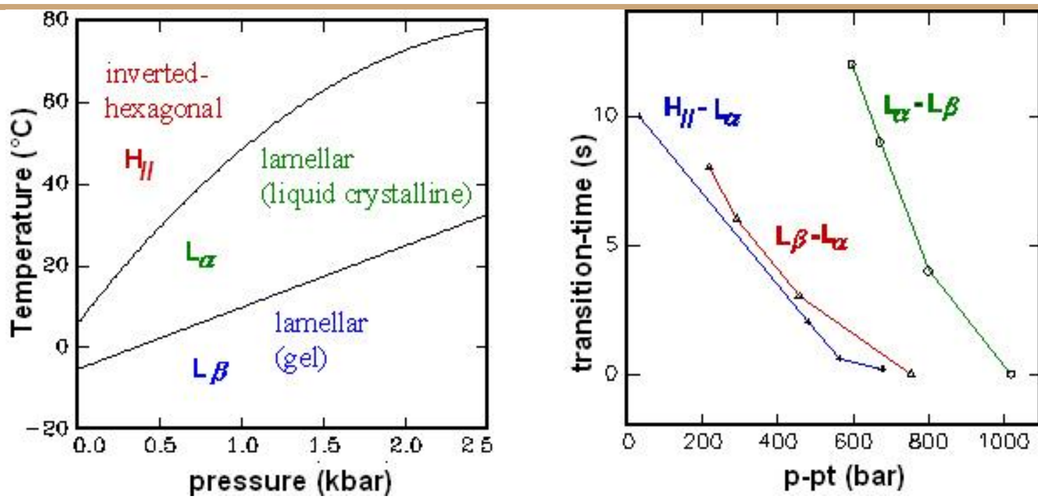


Figure 6: Phase Diagrams of MEA

From Figure 6 we can extrapolate that at low pressure and temperatures, MEA is a gel. This is unsuitable for the process. Therefore it is paramount to simulate atmospheric conditions to bring MEA within its liquid crystalline range. Furthermore, it is important to maintain the accepted efficient temperature characteristics throughout the process. "This is necessary because of the narrow temperature range in the [flue gas] sweetening process, and the efficiency of this process could be adversely affected if fluid temperatures are not maintained within this range."[21]

$$\rho \ = \ 0.039 \, kg/m^3 \ \ From \ Molar \ weights: 2898.7 \ \ kg \ air/kg \ CO2$$

$$At \ v \ = \ 283 \ m^3/min \ this \ yields \ 262634.8 \ min/tonne \ CO2 \ or \ 182.4 \ days/tonne$$

This number is desirable because the packing in the absorber and stripper need to be replaced every 6 months (around the same amount of time) [20]. Therefore 182.4 days is the estimated resonance time of the balloon with this technology.

A delivery of 10,000 CFM, or 283 m^3/min of air results in a CO_2 turnover time of 1 tonne in 182.4 days. Based on the absorptivity of carbon dioxide in MEA and the absorbent density this implies an MEA circulation rate of 5.73E-6 L/s, 8 orders of magnitude lower than in the Power Plant operation [18].

For the atmospheric air scaled down for 1/1000 of the power supply, the other changes made to the system are as follows:

- Blower rather than condenser
- Rich, lean amine power and compressor power further scaled down 1/10 due to low CO_2 flux in absorber (less work from each pump required).

	12% CO_2 Flue Gas	0.04% CO_2 Air
CO_2 Capture %	90	90
Rich Amine Loading	1.96 gmol/L	1.96
Lean Amine Loading	1.18 gmol/L	
Rich/ Lean Heat Exchanger duty	510 MW	510 kW
Reflux condenser duty	161.7 kW	
Blower Duty		74.7 kW
Gross reboiler duty	500 MW	500 kW
Net Reboiler duty	500 MW	500 kW
Lean Cooler Duty	287 MW	28.7 kW
Rich Amine Power	1741 kW	174.1 W
Lean Amine	1160 kW	116.0 kW
CO_2 Compressor Stages	4	2
CO_2 Compressor power	34845 kW	17.845 kW

CO_2 Pump Power	1001 kW	1 kW
Tonnes/ year Removed	343000	2

Table 2: Power Plant and Balloon Power Power Comparison

Mass Breakdown (assuming compact system)

- Carbon Steel: ~0.15 m^3 Yields 1900kg
- Stainless Steel: ~0.1m^3 Yields 748 kg
- 2 tonnes MEA: 2200 kg
- 200 kg pumps + compressor
- Total 5048 kg

Material/ Equipment	Cost ($CAD)
Monethanolamine (2.2 tonnes)	4000
Blower	10,000
Absorber (SS packed bed, 312 kPa, 5 cmx1m)	40,000
Stripper (CS, SS Packing)	68,000
Reboiler	70,000
Rich Amine Pump (Low Flow)	7,000
Filtration and Pipe Runs (~20m)	3,000
Compressors	1800

Gas Pump	400
Rich/ Lean Heat Exchanger (CS)	28,500
Total Capital Cost	232,700

Table 3: Cost Breakdown of Scaled Down Components

[16] cites a maintenance cost of approximately 12% of Power Plant maintenance cost. For the purpose of this paper 12% will be added to capital cost to yield a general idea of overall cost: Adjusted Cost = $260624. This is within an acceptable range due to the scaling down by a factor of 1000 for many of the components but increasing the blower duty to account for the lower concentration. The total cost for the full Power Plant is $20,000,000. Erring on the side of overestimation is viable in this design because the costs for developing a heated and pressurized cabin to house this system was not considered. Further research must be performed to select all of the equipment and size it properly to

Microchannel MEA

Carbon capture can also be achieved by microchannel reactors. These reactors enable the reaction of carbon dioxide with pure MEA solution, within channels that have physical dimensions within the millimeter range.

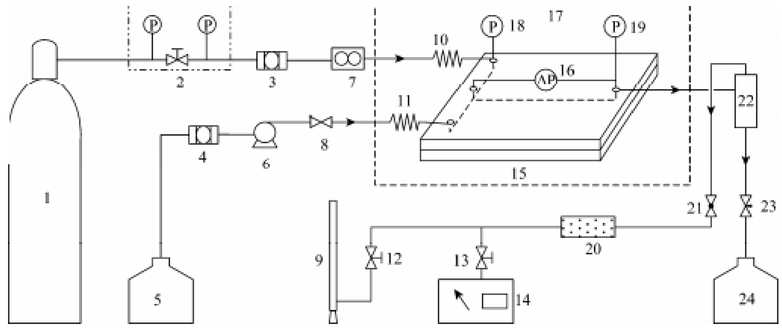


Figure 2 Schematic of the experimental setup for the CO_2 absorption process
1—gas cylinder; 2—pressure reducing valve; 3, 4—filter; 5—fresh solution tank; 6—constant-flow pump; 7—mass flow controller; 8—check valve; 9—soap film flowmeter; 10, 11—coil; 12, 13—adjusting valve; 14—CO_2 sensor; 15—microchannel reactor; 16—differential pressure transducer; 17—thermostatic waterbath; 18, 19—pressure transducer; 20—silica gel drier; 21—back pressure valve; 22—gas-liquid separator; 23—needle valve; 24—rich solution tank

Figure 7: Microchannel Reactor Set-Up [22]

This is an emerging technology so the applicability of the design is questionable until tested. However, the small surface area of the technology allows for more flexible design considerations.

Process

As is the case of a traditional plant MEA, the feed gas is pumped into the system at a rate comparable to the pumped MEA solution. The two reactants pass through a coil and into their respective inlets of the microchannel reactor, where they react along the 60 mm channel. Given that a feed gas of 30 percent CO_2 and a solution of 30 percent MEA enter the system simultaneously, the power allocated to pump MEA will be greater than that for the feed gas - this is because 2.2 moles of MEA is required for 1 mole of CO_2[21]. Also, since an operating pressure and temperature of 3 MPa and between 65 and 80 degrees Celsius, respectively, the reaction between CO_2 and MEA occurs almost instantaneously, with approximately 99 percent of CO_2 reacting with MEA. The final product of the reaction is MEAH+ and MEACOO-, which can be isolated by a gas-liquid separator and stored in a rich solution tank as an aqueous solution [21]. The gaseous product is fed through a silica gel dryer to remove traces of MEA, and then emitted to the atmosphere.

Constraints

There exists constraints that must be evaluated before a conceptual design can be achieved due to the atmospheric conditions at an altitude of 25 km. Using an industrial pump and allowing air to enter the system at 1000 slpm, it is assumed that CO_2 enters the system at 0.4 splm. This is estimated knowing that the atmosphere is composed of approximately 0.04 percent CO_2. Being that the process described above estimates that CO_2 enters the system at 300 slpm, air must be pumped into the system at 7500 slpm to capture the same amount of CO_2 per unit time. In working with such a small technology, it would be feasible to make up for this reduced efficiency by including more microcontrollers on the outer perimeter of the balloon. Another constraint is that the microchannel device is operating under a pressure and temperature of approximately 0.1 atm and -51.5 degrees Celsius, respectively. Under an ambient pressure of 0.1 atm and the same temperature, the reaction becomes less efficient, capturing only 80 percent of total CO_2 entering the system [21]. To conserve system efficiency, it is important that the microchannel and pipes are insulated to reduce the amount of dissipated heat per unit time.

Economic Analysis

The cost of one 316L stainless steel plate, 1 inch thickness by 4 inch length and width, is $0.48. The balloon has a surface area of approximately 4,820 square meters. We estimate that 10 percent of the balloon may be covered by the microchannel reactors. This allows for the use of approximately 482 microchannel reactors, costing roughly $232.00 [20]. This would apply an additional weight of approximately 1,000 kg onto the balloon. Assuming that each of the microcontroller reactor has it's own flue gas pump, this suggests that the CO_2 is being pumped at 193 slpm, or equivalently 101, 441 tonnes per year. The flue gas blower operates at 1415 slpm, each costing $935.00 for a total of $450,670.00.

Piece	Dimensions (“)	Weight (kg)	Total Cost ($)	Power (Kw)
316L Stainless Steel Plate	1 x 4 x 4	1,000	232.00	N/A
Flue Gas Blower		100	450,670.00	482
MEA		2.2 tonnes	4000.00	N/A

Table 4: Analysis of Microchannel Reactor Components

Cryogenic Liquefaction

Process

Pure gases can be separated from air by the cryogenic liquefaction process. It involves cooling air until it liquefies, then separating the different gases by distilling them at their various boiling temperatures. The process is effective but is energy intensive. The separation process requires heat exchangers and separation columns while the energy for refrigeration is provided by the compression of the air at the inlet of the unit [14].

To achieve the low distillation temperatures, an air separation unit requires a refrigeration cycle. The cold equipment must be kept within an insulated enclosure (commonly called a "cold box") to prevent freezing and the malfunction of the equipment. The cooling of the gases requires a large amount of energy to make this refrigeration cycle work. The power is usually provided by an air compressor [15]. The air separation process comprises the following typical steps [23]:

1. Air compression;
2. Air purification, to remove mainly water and carbon dioxide;
3. Heat exchange, in which air is cooled by outgoing cold products;
4. Distillation, to separate oxygen, nitrogen and argon;

5. Refrigeration (by work obtained from expanding some air from the heat exchanger into the low-pressure column);
6. The products, warmed by heat exchange with the air feed, are compressed externally with product compressors or can be pumped as liquid and vaporized to a desired pressure.

The separated products are often supplied to industrial companies nearby. End products can also be shipped in large quantities in gas cylinders.

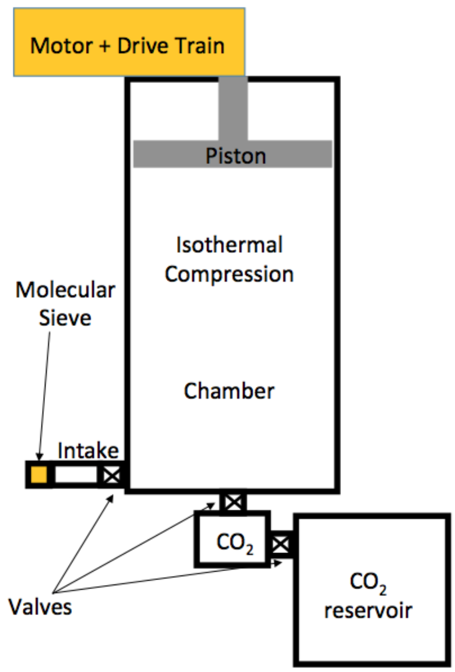
Constraints

The cryogenic liquefaction process described above is for a large plant on the ground. This process cannot be copied exactly at ~25 km in the atmosphere. It is not feasible since the weight would be much more than the high-altitude balloon could handle. Therefore, the first constraint is the size of this process. A larger system would be able to clean more CO_2 from the atmosphere but this increase the size as thus the weight of the system. Also, a larger holding tank would be able to hold more CO_2 but would also increase the overall weight that the balloon must carry.

Another constraint is operation and maintenance. The process of cryogenic liquefaction is not entirely automated. It must be supervised and each stage must be initiated for the process to continue. Lastly, once the reservoir is filled the process cannot be continued. The balloon must be brought down to add a new container.

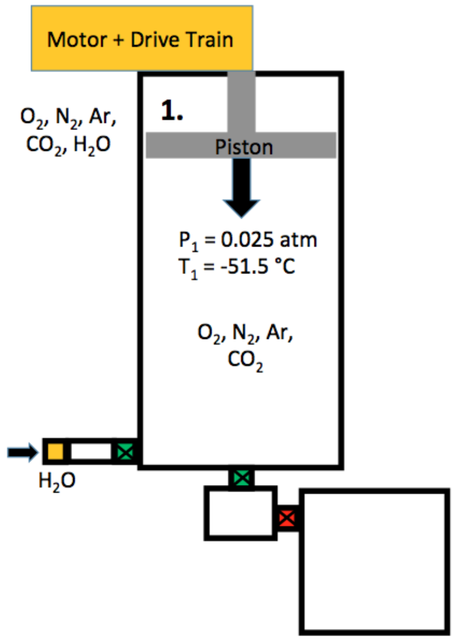
At ~25 km in the atmosphere the air is at an ideal temperature and there is no need to use a heat exchanger to cool down the air. However, the pressure is not at an ideal temperature. This will affect how much CO_2 can be cleaned. This can be overcome by increasing the size of the system, but this is undesired (as mentioned above).

High Altitude Process



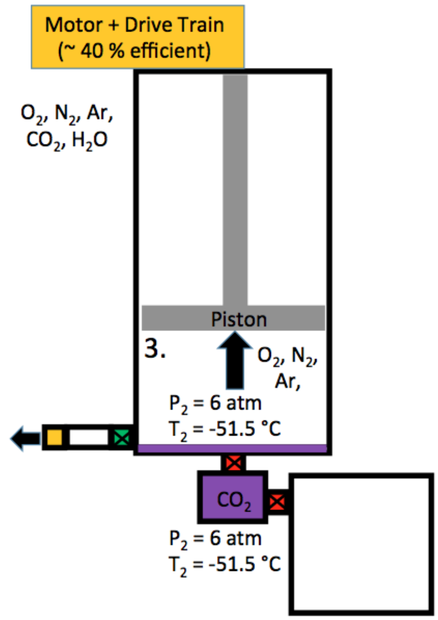
The cryogenic distillation system is shown in the figure with corresponding items. The following is an explanation of the step-by-step process that has been designed.

1) COMPRESSION

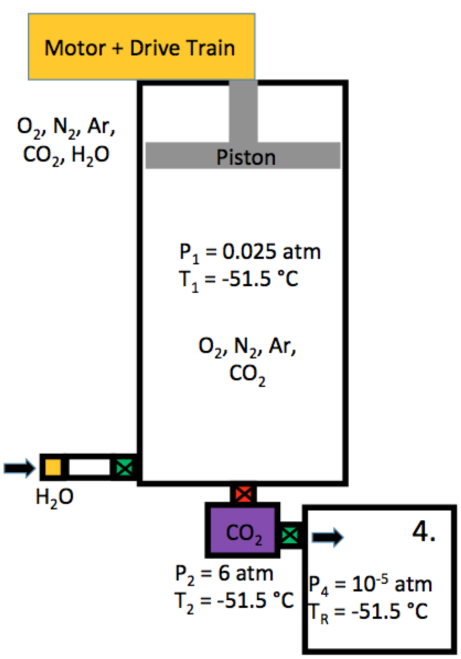


Here is the initial state of the system. Two of the valves are opened and one remains closed. The intake valve to the main chamber and the valve to the CO_2 tank is opened. At the temperature and pressure indicated in the figure, CO_2 is a gas and H2O is a solid. The other chemicals remain as a gas during the entire process. This equilibrates the chamber and the CO_2 tank with the surrounding. The air quickly fills the chamber and tank to the same pressure and temperature as the surrounding air. The air first passes through a molecular sleeve where the air gets dried of moisture. A piston driven by a motor compresses the air in the chamber to increase the pressure. By increasing the pressure, the CO_2 is converted into a liquid while the other chemicals remain as gases. The piston is driven downwards slowly at 2 seconds/cycle to allow heat to exchange with the surroundings. This kind of compression is an isothermal compression and assuming the air as an ideal gas the pressure can be calculated using P = nRT/V. Under isothermal compression conditions, the work for the cycle can be calculated by integrating the pressure with respect to its change in volume. Each cycle compresses a small amount of CO_2 into the tank. The process is repeated until the CO_2 tank is filled.

2) INTAKE

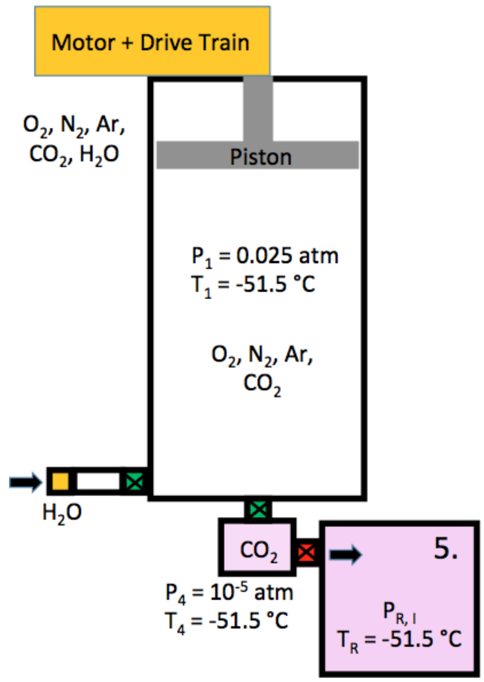


When the tank is filled will CO_2. the chamber is equilibrated once again with the surroundings. The intake valve is opened and the piston is raised as air fills the tank with the motor turned off. The pressure, concentration and temperature of the chamber return to the same as its surroundings as before.



As the process happens above, the tank of CO_2 can be pumped into a reservoir. The pressure gradient drives this process. The vacuum is set at a the same pressure and temperature of the tank in order for the CO_2 to remain a gas.

3) EQUILIBRATION



Once the tank is empty, the valve to the vacuum is sealed and the valve to the CO_2 is opened again. The pressure, concentration and temperature thus returns to the same as its surroundings to a state of equilibrium. All these steps are repeated until the reservoir is filled with a CO_2 liquid. The reservoir is initially at a medium vacuum (10E-5 atm) and it is pumped to this pressure on the ground. Cycling will continue until the pressure difference between the reservoir and the intermediate CO_2 container approaches zero. At this point there is no more driving force for the process.

The system will be composed of a 0.1 cubic meter compression tank, a small cubic mm intermediate CO_2 tank, and a 0.2 cubic meter CO_2 reservoir tank. Three valves and a piston and motor will be controlled by controllers cycling every 2 seconds. The weight and cost of these components are somewhat unknown, but we can expect each container to be under 50 - 100 kg at the very maximum, so a conservative 500 kg system weight is fair. Cost-wise, these components are simple, but will need to be custom machined. As a rough estimate, the system will probably cost somewhere in the ballpark of $10 000 to $100 000 to machine the parts.

Power

Number of Cycles	1 500 000
Min Energy (GJ)	2.08
Total Req. Energy (GJ)	3.3
Operating power (W)	1388
Total Time until tank is full (days)	35
Sequestration Energy (MJ/ kg CO_2)	917.762
Total Mass of CO_2 (kg)	3.63

Table 5: Results associated with Cryogenic Distillation/ Liquefaction

Public Relations

Like any project, there are a number of stakeholders that will be involved with this project, either directly or indirectly, whom will have to be accounted for in order for the project to be successful. A stakeholder analysis map was done, where each one of the stakeholders was ranked on it based on their expected level of interest in the technology, versus their expected level of influence on the project. It should be noted that in the analysis was done for the combined whole product, and not just the greenhouse scrubbing part. The map, as well as a brief description of each stakeholder, can be found in Appendix A

The conclusion of the analysis is that there are a number of key stakeholders that have both high interest as well as high influence, that will need to make sure are not conflicting with the project goals - in order for it to be successful. Those stakeholders are:

- Google - This is really the main competition to this project, and a very powerful one too. Google may not necessarily be in the business of greenhouse gases scrubbing, but they are in the business of high altitude balloons with similar goals to the main goals of our high altitude balloon. Because Google is a very powerful competitor, they could choose to affect this project by either harshly competing directly with it or buying it out.
- Government (as investors) - The government would be interested, and is sort of influential, however not very high on both accounts as an investor. This is still a very likely stakeholder to get funding from via direct purchases and/or grants.
- Government (as regulatory) - High on both accounts: they would be interested in regulating this technology for the best of the public's interests, as well as being very influential on the project in terms of the decisions they make. We need their permissions and pass their regulations.
- Airplanes (Traffic) - Airplane companies are both influential and interested. We will need to coordinate with them the wireless energy beam that will be sent to power

the balloon, as well as raising and lowering the balloon (if it needs to be brought down for maintenance).

- Army - The army has a very high influence, and a high interest. This technology is a powerful one that could be a national security issue from many perspectives, and that's the army's job! So their influence would be very high because of that. On the other hand, they would also be interested in taking advantage of this technology (according to Erin, the project champion, the US Army is already an interested investor).
- FCC - Very influential, as they will most likely be the regulatory body that would regulate the product.
- Telecom Companies - This is the main client: they specify design requirements so have high influence. We are putting up their technology for much cheaper costs, so they also have a very high interest in this project.

This is not to say that the other stakeholders not mentioned above are not important. They are indeed important and this is why they are still outlined in Appendix A. However, due to them either not having a strong interest, or interest influence (or both!), they are lower priority to the project than the ones outlined above. They are still included, and should always be considered as much as it is possible, as it is the right and ethical thing to do. Ideally, every single stakeholder should always be a winner in order for this project to be 100% successful.

Conclusion

Different carbon capture technologies have been researched in the interest of attaching them to a high altitude balloon to mitigate climate change. Planting trees has been considered and some innovative alternative technologies have been presented. The most promising carbon capture technologies were described and some of their limitations were outlined. Based on atmospheric conditions at 25 km altitude, along with design conditions required for chemical and physical changes in composition, the following estimates for outputs were generated.

	MJ/Kg CO_2	Mass (kg)	Cost ($CAD)	Power (W)	Time (per tonne of CO_2)	Estimated Balloon Resonance Time
Industrial MEA	790	5048	260,624	$5x10^5$	183 days	183 days
Microchannel MEA		1,100	454,902	482,000		
Cryo. Liquefaction	917	< 500	10 000 - 100 000	1388	26.4 years	35 days
Average Tree	N/A	N/A	4000	N/A	140 days	N/A

Table 6: Average Tree Info for an acre of trees loading 13 pounds of CO_2 per year [19]

Thus, it is clear that further research must be done to select equipment sizes and develop full system models to simulate actual power usages carbon dioxide loading capability. For future, tests on actual prototypes will yield best results for representation of implementation.

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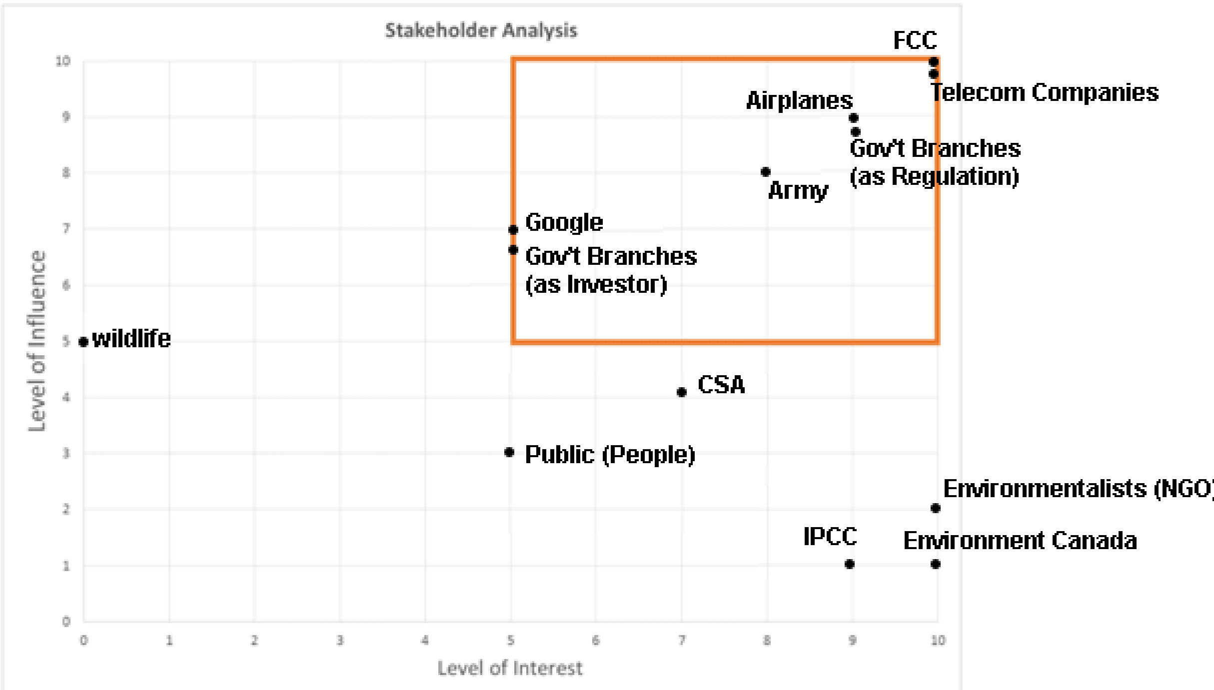
Appendix A - Stakeholder Analysis



Stakeholders Analysis Map (Level of Influence vs Level of Interest)

Public (People)

This is the public perception – who may choose to say NIMBY (Not In My BackYard). People are interested in what is going on in their neighborhoods; however, they require extensive lobbying to produce results (whether supportive or against).

Wildlife (like birds)

Animals themselves have no interest or influence; however, they're a safety influence on our design and operating conditions. For instance, the beam of energy will need to shut off to not kill birds.

Google (competition)

A company like Google have the power to buy-out our or similar technology. As they are doing something similar, they will be mildly interested in this technology.

Canadian Space Agency (CSA)

CSA will have a good amount of interest because we are essentially taking away satellites that go up. They perhaps may not have as much influence on this project though.

Army

A high influence, and a high interest. They will want to take advantage of this technology (according to Erin, the US Army is already an interested investor)

Telecom Companies

This is the client: they specify design requirements so high influence. We are putting up their technology for cheaper so high interest.

Government Branches: (as regulators)

High on both accounts: they can use the technology in many different areas, and we need their permissions and pass their regulations.

Government Branches: (as investors)

Sort of interested, sort of influential. Likely to get funding here.

Airplanes (Flying Traffic)

Airplane companies are both influential and interested. We will need to coordinate with them the energy beam, as well as raising and lowering the balloon.

ITU, FCC: (Federal Communications Commission)

Very influential, as they will most likely be the regulatory body that would regulate the product.

Environment Canada

Not a lot of influence, but they will be interested in the technology, GHG reduction, and CO_2 scrubbing.

IPCC

Low influence high interest. They would be interested in knowing our GHG reduction technology and numbers, but they won't really change much.

Environmentalists (NGO)

Low influence high interest, same as IPCC.

This list also includes famous public figures from the scientific community. Those figures have a medium influence & interest. They could promote and publicize the technology, and they would also be interested in also the climate change factor (think Bill Nye, Chris Hadfield, Neil Tyson Degrasse, etc)

Appendix B - Background Information

Balloon Background

The background information on our balloon is comparable to that of a weather balloon. It is almost the same idea as both float into the air and provide data for a 3^{rd} party located on the surface. A weather balloon is generally filled with around 300 cubic feet of helium air and tends to be roughly 5 feet in diameter when launched at ground level. In around an hour the balloon can travel to around 100,000 feet or 30km. At that point the balloon can reach a size of 32 feet or 10 meters. The difference with a weather balloon is, its purpose is to rise to a 100,000 feet, which causes a decrease in pressure to expand the balloon to the point of failure. This however is not the case with our CO2 scrubbing balloon. Ours will be held in place at a known height that is safe for the balloon, but also allows proper atmospheric scrubbing and steady, reliable transmitting of data to take place. Weather balloons are usually made of latex a durable and affordable material. Thrusters will be used on the balloon to hold the balloon in place making it safe and easy to locate from the ground in case of problems. It will be easy to calculate the thickness required to maintain the balloon at the desired height as it will not be moving and should not encounter any unexpected problems that high up in the atmosphere. Things like weather and air traffic should not be a factor.

Hydrogen and helium can be used as the gas to fill the balloon. However, it is more common today to find helium in these types of balloons, although it is more expensive it is an inert gas meaning it is less reactive and therefore less dangerous. Below is an example of what could happen if hydrogen is misused.

Figure B1 - Hydrogen Explosion

The thrusters and machinery on board that are used to transmit the GPS, and cellular data will be powered using energy transmitted from ground stations. This energy will allow the balloon to remain in place as long as required. While the CO_2 scrubbing is taking place a weight counteracting system will have to be put in place to insure the weight of the balloon remains constant or more energy will have to be sent to increase the power of the thrusters insuring location is not altered.

Gas Composition at Low Altitudes

Due to turbulent mixing, the composition of gases throughout the first 100 km of earth's atmosphere is relatively homogenized. This means that the molecular weight of this region of the atmosphere is relatively constant, and it is only until 80 to 120 km that a transition regime occurs. Only after that will molecular diffusion play more of a role in the distribution of gases as a function of altitude. This leads heavier gases to settle near 100 – 120 km, and the probability of finding a massive gas molecule will decrease with increasing altitude. [AB1]

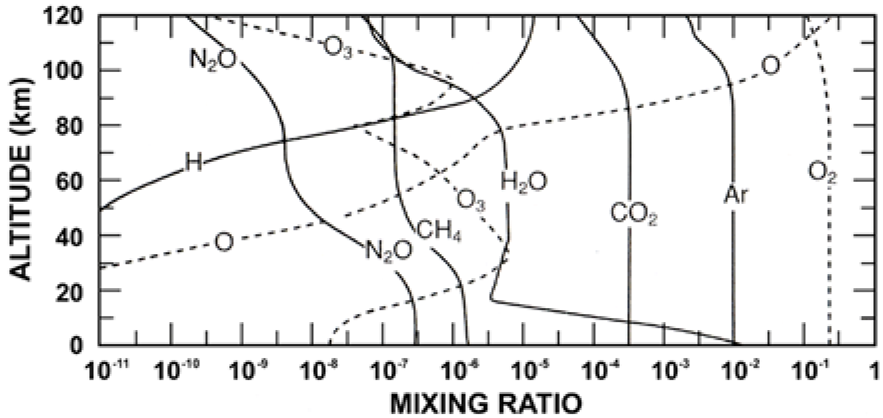


Figure 2 - Mixing ratio (mole fraction) of gases as a function of altitude

Key gases with a high Global Warming Potential (GWP) that can be targeted near an altitude of 25 km are: methane, nitrous oxide, carbon dioxide, perfluorocarbons (PFCs), hydrofluorocarbons (HFCs). Presently the current global average of carbon dioxide emissions are 400 ppm which is the largest volume fraction of greenhouse gas in the atmosphere. Methane in northern latitudes near 30 km in altitude is present at 500 ppb (2008) [AB2]. Nitrous oxide in mid latitudes near 30 km in altitude is present at 120 ppb [AB2]. There are many HFCs that have a high GWP, but a few key players are HCFC-22, HFC-23, HCFC-142b, and HFC-152a which are all gases listed in the Kyoto Protocol as greenhouse gases. HCFC-22 is the most abundant GHG present at around 100 ppt (1999) [AB2]. Comparatively, the other HFCs are present in about one order of magnitude less in concentration.

PFCs and SF_{6}- have the highest GWP due to their large cross-section for absorbing radiation. For example 1 kg of SF_6 is equivalent to 22,800 kg of CO_2 and has a lifetime of 3200 years in the atmosphere [AB3]. PFCs in general have a GWP ranging from 7,390 – 12,200. The largest volume per cent PFC in the atmosphere is CF_4 which as of 2008 was present at around 40 ppb. CFC-11 and CFC-12 were present in 1998 in 250 and 550 ppt respectively [AB2].

The primary cleansing agent for removing gases such as nitrous oxide, methane, VOCs, and CFCs from the lower atmosphere is by reacting the compounds with a hydroxyl radical (OH) [AB1]. OH can be produced when high energy UV-radiation causes ozone to dissociate. This dissociated ozone can react with gaseous water to produce a hydroxyl radical capable of reacting with the above pollutants. Other mechanisms of producing OH involve the dissociation of peroxides or formaldehyde and do form in the upper atmosphere.

Overview of CO_2 Scrubbing

Carbon capture and sequestration is used predominantly in power plants to reduce emissions. Pre-combustion carbon capture consists of trapping the fossil fuel before it is burned. This is achieved by heating the fuel in pure oxygen until it breaks into carbon monoxide and hydrogen, then fed through a catalytic converter [AB4]. The resulting gases are bubbled through amine until the CO_2 sits on top for capture.

The oxy-fuel carbon capture method removes the need for a converter by burning the fossil fuel in oxygen. The resulting hydrogen and CO_2 can be separated by cooling and compressing the gases. This method reduces up to 90% of a plant's carbon emissions but is more expensive, as large quantities of oxygen are used [AB4].

Post-combustion filtration cuts up to 90% of carbon emissions and is a popular option for industry as it can be installed as a retrofit to a smokestack. There are three main filter methods of capturing CO_2 post-combustion.

a) The filter comprises of a solvent made up of either monoethanolamine (MEA) or aqueous ammonia [AB4]. The CO_2 mixed with other flue gases bubbles into the solution and is heated out into a separate compartment, leaving almost pure CO_2.

b) The CO_2 is selectively adsorbed onto a solid surface. It requires less energy than absorption to liberate the pure carbon dioxide.

c) A membrane selectively separates the CO_2 from the other gases by permeating it through a filter. This offers the lowest energy-cost. [AB5]

These carbon capture technologies are still relatively new and undergoing research. As of 2013, there stages of development are as follows.

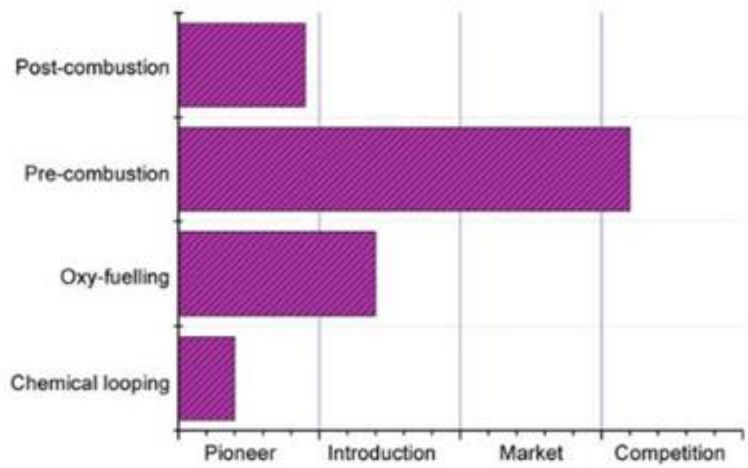


Figure B3 - Stages of development for each of the technologies considered for carbon capture

The main challenges of post-combustion CO_2 capture are as follows: "A major effort is needed to design more effective catalysts, stable to gas pollutant emissions and to high temperatures, and providing lower costs than current catalysts based on MEA (monoethanolamine)." [AB5] The costs of these technologies can be compared over their development. Post-combustion has a relatively high cost but thanks to research into efficiency the cost has been lowering.

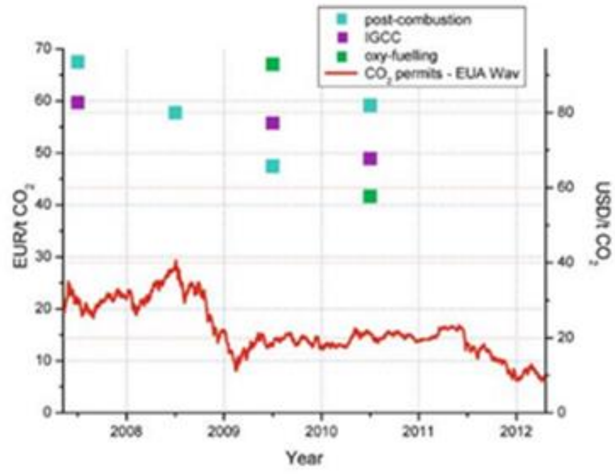


Figure B4 - CCS costs per ton of CO_2 for different technologies and evolution of the European Union Emission Trading Scheme for CO_2 permits 10-15% of the cost includes that of transportation [AB5]

Regulations

In order to set a helium balloon in the sky with laser technology, certain regulations must be adhered to. Since the area of interest is in Canada, the regulations that are included here are from the government of Canada. There are three clear regulations that are to be obeyed. The first is in terms of laser pointers, the second relates to large unoccupied free balloons, and the third is in accordance with payloads. We will examine these three in order of importance.

Laser Pointers

The government of Canada has taken a strong stance against aiming a laser at an aircraft. Under law, pointing a laser at an aircraft is illegal and a criminal offence. Under the Aeronautics Act, if you are convicted of pointing a laser at an aircraft, you could face up to $100,000 in fines, 5 years in prison, or both [AB6]. A laser that shines into an aircraft could distract the pilot by creating glare, and even cause temporary blindness, especially during the night. This could cause serious injury or death. The government does provide a notice of proposal form that can be completed is one plans to project a laser into the sky [AB6]. Therefore, it is not impossible to do so.

Unoccupied Free Balloon

Under the Aeronautics Act, Regulations Respecting Aviation and Activities Relating to Aeronautics, Section **602.42, "**No person shall release an unoccupied free balloon having a gas-carrying capacity of more than 115 cubic feet (3.256 m^3) except in accordance with an authorization issued by the Minister pursuant to section 602.44." [AB7]. Therefore, the balloon must fall under a carrying capacity of 115 cubic feet or receive authorization by the Minister of Transportation.

Payload

Canada does not have any strict regulations in terms of payloads if they are carried down by a parachute or other device that is able to slow the descent to less than 3.5 m/s [AB8]. If attaching a parachute to the balloon is unfeasible, a device will need to be designed to slow the descent to less than 3.5 m/s.

Climate Change Overview

Scientists have studied climate change extensively, and suggest a great increase in atmospheric carbon dioxide over the past 1,950 years – highly suggestive of human involvement since the start of the Industrial Revolution [AB9]. NASA has performed studies that are indicative of the heat-trapping nature of carbon dioxide and other gases in the atmosphere: infrared energy delivered from the sun is being absorbed, and trapped in the planet's atmosphere because of CO_2 [AB9]. Evidence of rapid climate change includes rising sea levels, increasing global surface temperatures, and ocean acidification [AB9].

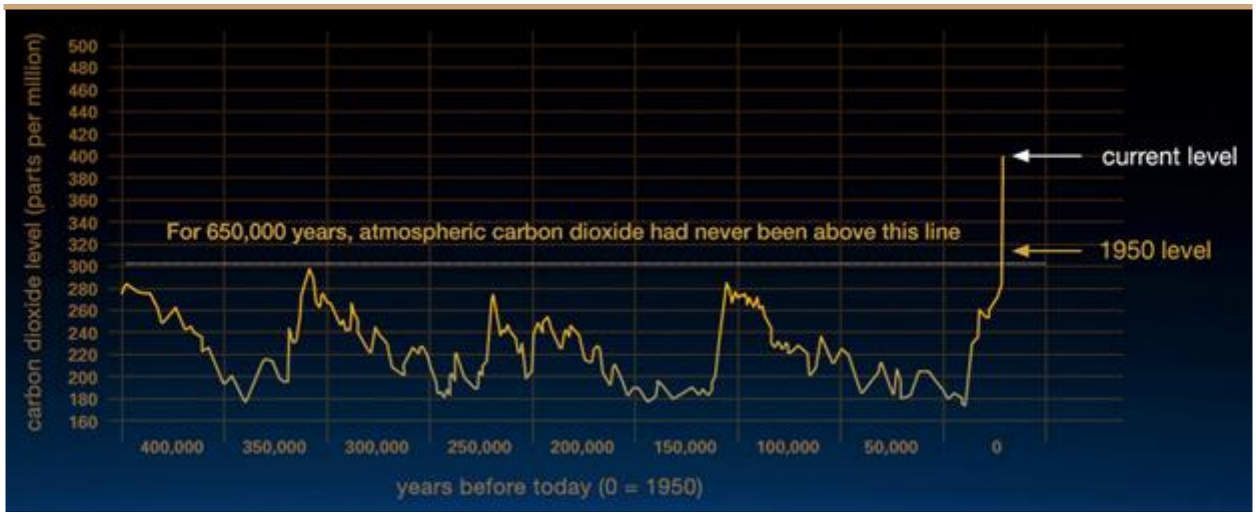


Figure B5 - A timeline of atmospheric CO_2 level (in ppm), and how it has greatly increased in the last 1,950 years

Ocean Acidification

Research from NOAA (National Oceanic and Atmospheric Administration) shows that the ocean absorbs 25% of the CO_2 being produced [AB10], which has increased the oceans' acidity by about 30% since the start of the industrial revolution [AB11]. Acidification of the world's oceans causes seawaters to warm, which can be devastating to sensitive ecosystems like the coral reef. Increasing temperatures cause coral to bleach, and reduces their ability to combat disease [AB13]. The coral reef accounts for over 25% of the world's fish biodiversity, is associated with between 9 and 12 of the world's fisheries, and has an estimated $5.5 billion dollar annual net value [AB12]. Canada is also greatly affected by acidification, which can affect organisms' ability to reproduce and thrive – an example being shellfish, which rely on carbonate ions to form their shell and skeleton [AB14]. Having relied so heavily on the ocean's resources as a source of food, recreation, transportation and medicine; groups such as IUCN (International Union for Conservation of Nature), actively support reduction of CO_2 emissions [AB11].

Stats of CO_2 emissions

The amount of CO_2 being produced varies across regions of the planet, with North America being the second largest contributor with over 7,000 tons of CO_2 in 2014 (Asia Pacific delivering over 16,800 tons in 2014) [AB15]. Specifically looking at Canada, the emissions are understood to vary according to factors including population size, economic activities, and amount of resource extraction [AB16]. According to Environment Canada, Ontario and Alberta are the leading provinces for CO2 commissions, with Ontario's having lesser contribution 2013 than both 1990, and 2005 [AB16].

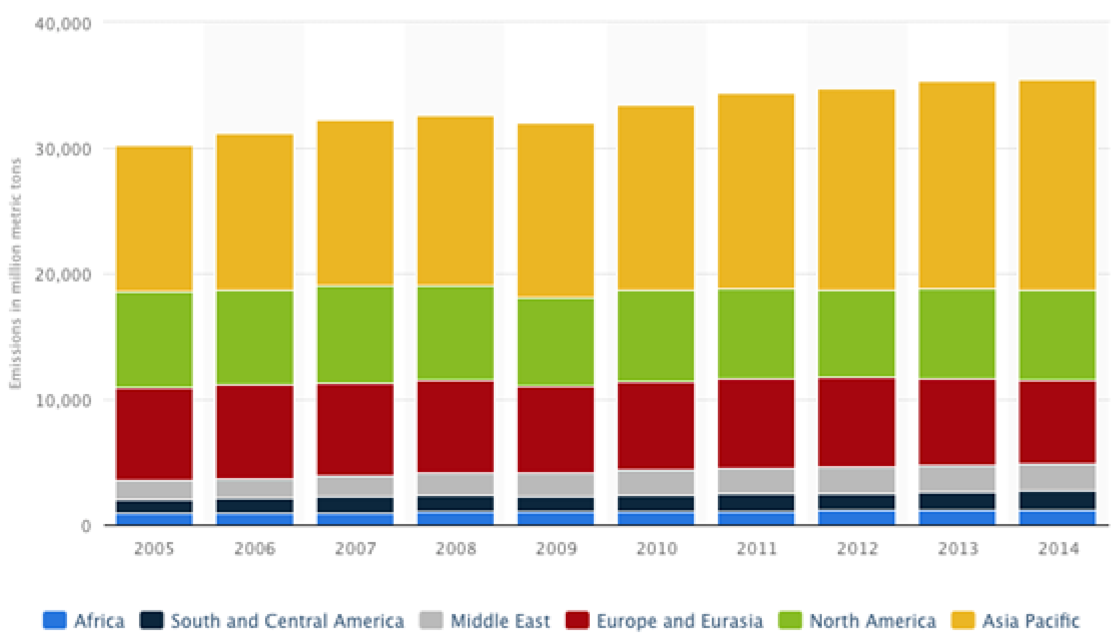


Figure B6 - Statistic worldwide CO_2 emissions produced through consumption of gas and coal between 2015 and 2015

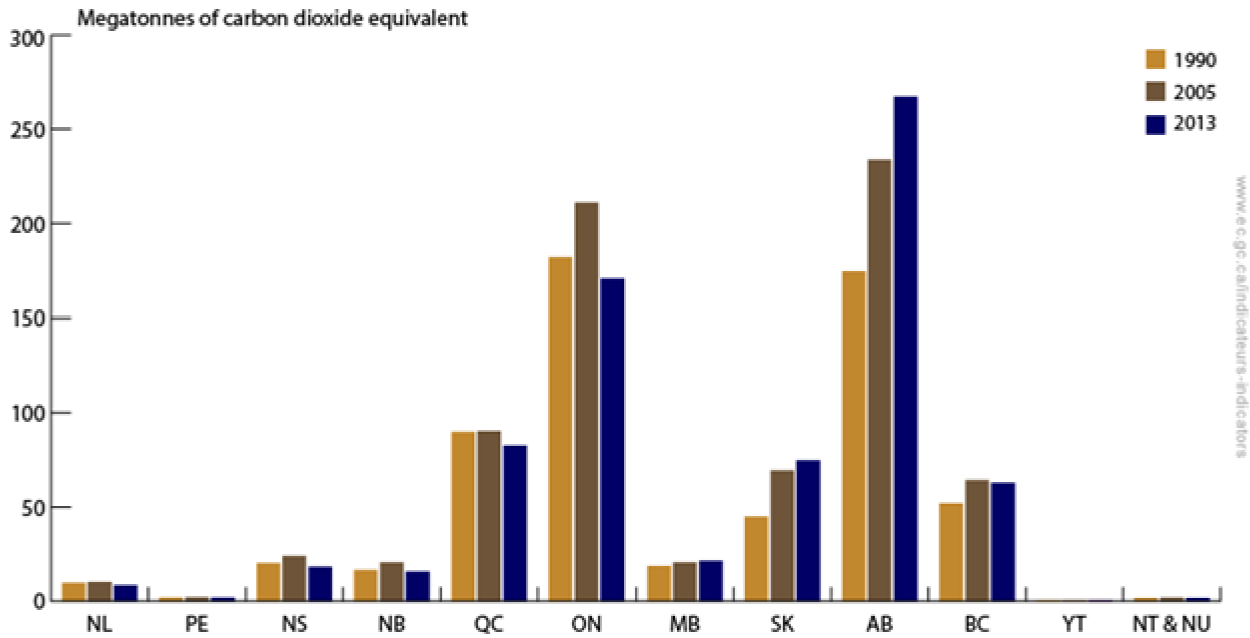


Figure B7 - Greenhouse gas emission by province and territory of Canada; for the years 1990, 2005, and 2013

Wireless Power Transmission

Wireless power transmission is a technology which allows for a wireless beaming of electric power from one source to another. This means doing the transmission through the vacuum of space or air, and without the use of wires or any other substances. The technology was first analyzed by Nikola Tesla in the early beginnings of the 20th century. But what's the use of such technology? It's estimated that up to about 30% of power is in fact lost in the existing way of transmitting energy through wires due to friction. Having this technology in a wireless form doesn't just solve the friction problem, it also helps bring down the cost of transmitting energy and helps unlock potential for other application that are now dependent on other sources of energy generations. [AB18][AB19]

When it comes to wireless power transmission, there's a number of existing technologies that exist that do that. For the purpose of this project, the team will be focused on those that have a high range of transmission, given the nature of our project.

The scope of this background research will thus be focused on a technology called Microwaves Power Transmission (this decision was determined with the project champion).

Microwaves Power Transmission

Microwaves Power Transmission is currently the technology of using frequencies of around 2.45 GHz to beam electric power from one place to another. In most applications the microwave system consists of four major parts: (1) the conversion of d.c. power into microwave power, (2) a transmitting antenna to convert the microwave power into a narrow beam, (3) a segment of space in which the microwave power is transmitted, and (4) the absorption and conversion of microwave power back into d.c. power at the point of reception. [AB17]

This technology will be used to transmit energy to flying hot-air balloons at an altitude of about 20,000 m in order to power the devices on board of that balloons. The devices will consist of ones for GPS and mobile communications, and others for the CO_2 scrubbing technology the group decides to opt-in for.

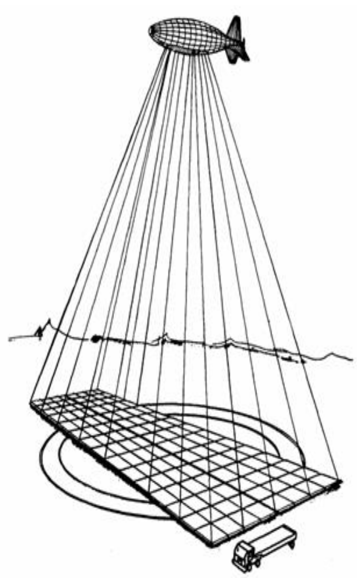


Figure 8 - A sketch illustrating the transmission of power from the ground to a flying vehicle at an altitude of 20,000 m (which is similar to the project the team is working on) [AB17]