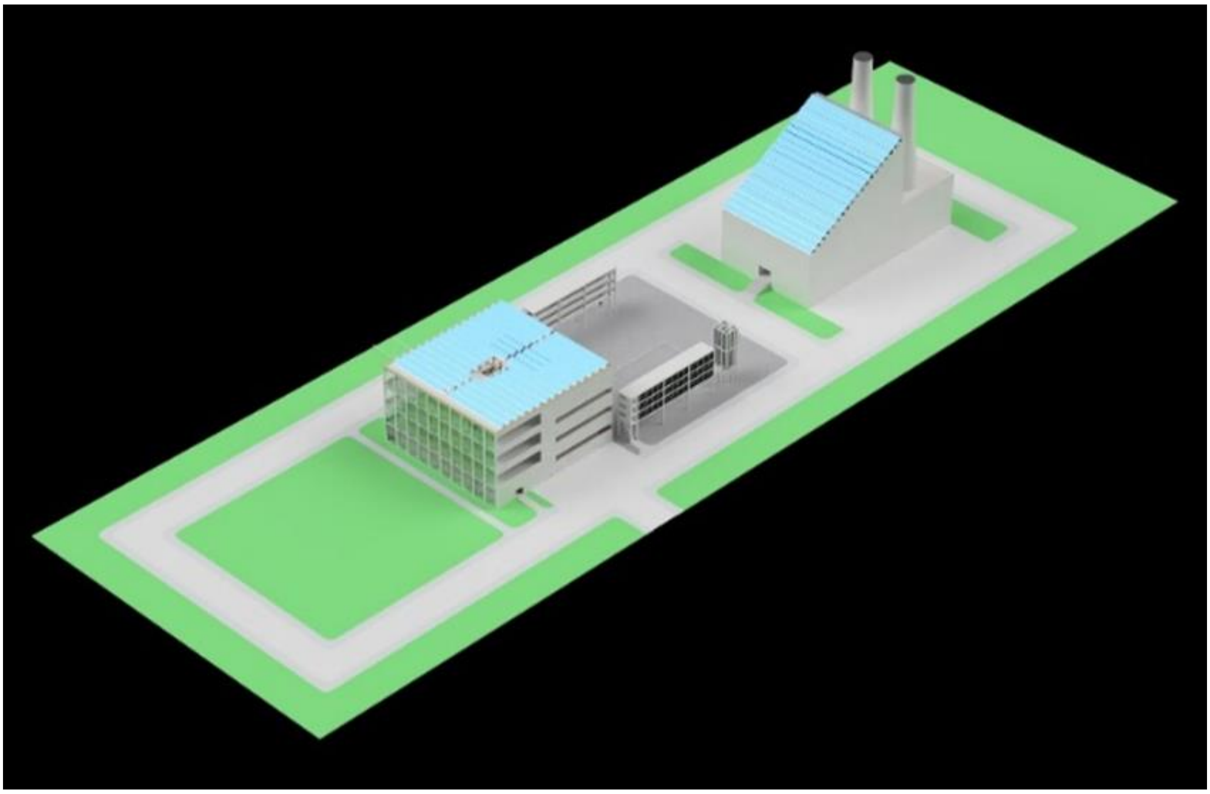
School of Engineering
Integrated Design Project 2 Assignment 1
Concept Design
2021/22
Group: 52
Direct Air Capture Facility in Guadalajara



10/03/2022

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Word count:10528

STATEMENT OF CONTRIBUTION

Name	Student ID	Contribution	Signature	Contribution
Yassin	1915861	Group Coordinator & Report Team	Y.S	Normal
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Peer Assessment Marking	Adam	Ethan	Harpreet	Hilton	Ibrahim	Yassin			total points	Valid?
worked harmoniously	5	5	5	5	5	5			30	TRUE
contributed to decisions	5	5	5	5	5	5			30	TRUE
communicated frequently	5	5	5	5	5	5			30	TRUE
listened to others	5	5	5	5	5	5			30	TRUE
took responsibility for tasks	5	5	5	5	5	5			30	TRUE
solved problems	5	5	5	5	5	5			30	TRUE
attended meetings	5	5	5	5	5	5			30	TRUE
has good attitude	5	5	5	5	5	5			30	TRUE
contributed substantially	5	5	5	5	5	5			30	TRUE
Score per person	5	5	5	5	5	5				
Rank	3.5	3.5	3.5	3.5	3.5	3.5				
Suggested contribution level	Normal	Normal	Normal	Normal	Normal	Normal				

CONTENTS

EXECUTIVE SUMMARY

In this report, our objective was to create a concept design for a DAC (direct air capture) facility in Guadalajara, Mexico. Our main goal was to produce a carbon-neutral and sustainable facility that would capture 5000 metric tonnes of CO2/year from the air. Within this report we outline the steps we took to arrive at our final design.

To begin our project, we allocated roles within the team and subject focuses based on our Belbin test results. In this project management section, we also explore the impact the test had on our group work in addition to planning our time across the 6-week time frame. Using a Gantt chart, we were able to structure and guide ourselves through the tasks according to our deadlines and targets to launch our solution as efficiently as we could.

Following this initial section, we began our research which was broken down into sections for each team member. There are two main types of solvents used for absorption: liquid or solid solvents. We are using liquid sodium hydroxide as our solvent for absorbing CO2 from the ambient air in our facility. This process is followed by a desorption process which varies depending on the sorbent used, whether it be a solid sorbent (usually amine based) or a liquid solvent, the most common being MEA. The most commonly used liquid solvent is MEA, an amine-based solvent. In this process the solvent is cycled through an absorber, heat exchanger and desorber and in the desorption section the carbamate formed during the absorption reactions is heated at temperatures just below 80 °C to release CO2 which is passed through a condenser and collected. The carbon dioxide will be transported from the desorption section of the facility to the storage and reuse sections of the DAC facility.

Following our research, we were able to analyse the information in further detail using the objective tree and requirements specification following four key criteria or directives – functional, technical, customer, and quality. This thorough research allowed us to progress onto the concept design whereby the design team brainstormed initial ideas against the design rationale which then progressed on to a final schematic.

To conclude the report, we delved into the risk management aspect of the project and carried out a few exercises to help negate any potential risks we could encounter. By carrying out these activities not only were we aware of possible risks, but we are able to pre-empt and offer safer and more practical solutions due to the critical analysis. Finally, we provided a life cycle analysis of our concept design in Guadalajara and outlined potential benefits through our PEST analysis as well as our aim to progress the United Nations Sustainable Development Goals.

PROJECT MANAGEMENT

People

Belbin results

Name	Belbin Team Roles	Myers-Briggs Test
Yassin Seddik	Implementor/Coordinator	Protagonist: ENFJ-A
Hilton Dien	Team Worker/Specialist	Entrepreneur: ESTP-T
Adam Wilkes	Monitor Evaluator/Team Worker	Defender: ISFJ-A
Harpreet Dhillon	Implementor/Team Worker	Consul: ESFJ-T
Ethan Chung	Shaper/Complete Finisher/ Specialist	Protagonist: ENFJ-A
Ibrahim Kabir	Coordinator/Specialist	Campaigner: ENFP-A

Table 1. *Belbin and Myers-Briggs test results.*

Impact on group work

Initially we had discussed which roles we connected least with in an attempt to manage our weaknesses and work to each of our strengths. The results from the Belbin profile test allowed us to delegate our roles with greater ease and as the group's personal thoughts were in line with the results of the test allocated each team member's role accordingly. This encouraged a boost in team morale and trust which allowed us to work more productively. Overall our strategy was effective as the work load was evenly distributed, deadlines were kept in line with our Gantt chart forecast and morale was kept at a positive level throughout the project. Alternatively, we could have used the Myers Briggs results however we felt the Belbin profile test provided more detailed and appropriate results for our project.

Design Thinking

As a group we decided the "assumptions and questions" activity would be most effective identify and prioritize what assumptions were being made, what we've been guessing, and what our team still didn't know. We also made questions and collectively positioned them on the grid in relation to risk and certainty. The notes in the upper right quadrant indicating high risk and uncertainty were then priorities we tackled first. The IBM activity was important as it served as the driving force for inclusion and collaboration so all the voices in our group were heard and understood in addition to providing structure to our creative design thinking.

Planning

Gantt Chart

Planning the project was key to our success as we had to set SMART targets whilst understanding what stepping stones and milestones we had to complete within our short time constraint. These small tasks of planning enabled us to fill out the Gantt chart and incorporate the required time frames for each milestone. Using the project management toolset, the structure and guidance paved the way for us to launch our solution.

Event ID	Activity Type	Description	event ID (if the event cannot start before the preceding event finishes)	Event duration (days)	date (auto populated if there is a preceding event in column H)	End Date (auto populated)
1	Completed	Meet group and introduction to design specification		5	02/02/22	09/02/22
2	Completed	Project management and profiling exercises		5	02/02/22	09/02/22
3	Completed	Project plan spreadsheet and role allocation		3	10/02/22	15/02/22
4	Started	Research-Journal club		5	10/02/22	17/02/22
5	Reporting / Documents	Objective Tree		1	14/02/22	15/02/22
6	Reporting / Documents	Sustainability exercises		3	17/02/22	22/02/22
7	Milestone	Feedback on Objective tree to proceed to Design with Academic mentor		3	21/02/22	24/02/22
8	Reporting / Documents	Health and Safety Risk Assessment-HAZOP		2	24/02/22	28/02/22
9	Reporting / Documents	PEST analysis		2	24/02/22	28/02/22
10	Design	Complete Design and collate individual work		3	28/02/22	03/03/22
11	Milestone	Refining requirements and design ideas with Academic mentor		1	03/03/22	04/03/22
12	Milestone	Present additional design impact exercises		1	03/03/22	04/03/22
13	Design	Finalise Design		4	07/03/22	11/03/22
14	Reporting / Documents	Complete Report		4	07/03/22	11/03/22
15	Reporting / Documents	Complete Presentation		4	07/03/22	11/03/22
16	Assessment	Submit Final Assignment		1	10/03/22	11/03/22
17	Reporting / Documents	Complete peer review exercise		1	10/03/22	11/03/22
18						

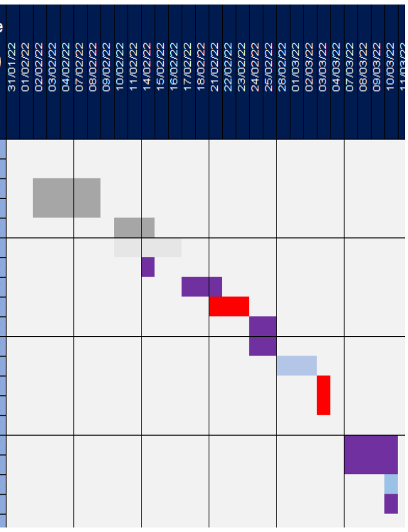


Figure A. *Gantt chart detailing our activities across the 6-week timeframe for our concept design*

RESEARCH

For this assignment we were tasked as a group to produce a concept design for a Direct Air Capture facility in a designated city – ours being Guadalajara, Mexico. Guadalajara is the second largest urban centre in Mexico and is also one of the most polluted in Mexico averaging 179mg per cubic meter of suspended particulates, which exceeds the maximum recommendation of 90mg by the World Health Organisation. Due to the enormous number of vehicles operating in the city, it exceeds pollution standards 90% of the time (Oh, Cook and Townsend, 1999) [1]. A DAC facility would be ideal in Guadalajara as current measures to reduce carbon emissions are ineffective. CO2 is extracted directly from the atmosphere using direct DAC methods. CO2 can either be permanently retained in deep geological formations (resulting in negative emissions of carbon removal), used in food processing or mixed with hydrogen to create synthetic fuels. Liquid and solid DAC are the two technologies currently being utilised to capture CO2 from the air. Liquid systems remove CO2 by passing air through chemical solutions (such as a hydroxide solution). The device uses high-temperature heat to reintegrate the chemicals into the process while returning the rest of the air to the environment. Solid sorbent filters that chemically bind with CO2 are used in solid DAC technology. The concentrated CO2 is released when the filters are heated and placed under a vacuum, and it is then caught for storage or utilisation [2]. Our facility will have the capacity to capture 5000 metric tonnes of CO2/year across a 30,000m^2 site outside of the metropolis area with a life span of approximately 10 years.

There are two main types of solvents used for absorption: liquid or solid solvents. We are using liquid sodium hydroxide as our solvent for absorbing CO2 from the ambient air in our facility. The chemical equation for this is $2NaOH{+}CO2{\rightarrow}\ Na2CO3{+}H20$. In Guadalajara the air contains 350-450ppm of CO2 (Martha Georgina Orozco-Medina, August 2020) [3]. Currently it is believed that a capture efficiency of 50% is possible using NaOH (Rackley, 2017). With a small improvement in technology and by using larger absorber towers this efficiency could be increased, and it would be reasonable to expect 250ppm of CO2 (62.5%) to be absorbed from an average of 400ppm of CO2 from ambient air. A pump would be needed to pump the solvent for the absorption process. To reduce energy consumption, we will use a 5% solvent pump duty cycle, this means that each section of the packing is wetted with NaOH only 5% of the time. The downside of this is that the capture performance is reduced to 85% (Rackley, 2017). Through further research it is believed that a capture capacity of 20 t-CO2-/m2-year can be achieved (Rackley, 2017) [4]. This would mean that to capture 5000 tonnes of CO2 a year an area of 250m2 would be required. But because we only have an 85% capture performance, and the facility may not operate at 100% efficiency we are aiming to have 300m2 of fans. This would require the facility to be capturing air 24/7 and it would be expected that the volumetric flow rate of air for each blower fan to be around 33,000m3/h. This would allow for 571kg of CO2 to be absorbed per hour. This would require a blower fan similar to the CMRS-1000-6T-25 IE3 which has an efficiency of 73.1% at a power of 17.2kW and this produces a flow rate of 37,016 m3/h. The fan diameter needed for this would be around 1m (Sodeca, n.d.) [5]. Carbon engineering believe that it would require 8.8GJ of energy per tonne of CO2 absorbed and so using this estimate it would require 12,200MWh/5000t-CO2 to run the facility for a year (Recharge, 2021) [6].

Desorption processes vary depending upon the sorbent used whether it be a solid sorbent (usually amine based) or a liquid solvent. Temperature Vacuum Swing Desorption is the most effective method for disassociating CO2 from a solid sorbent. A mild vacuum is applied to the system allowing for lower temperatures to be used, resulting in a lower specific energy requirement; this method also allows for better regeneration of the sorbent- over 85% regeneration at 60 °C (Zain Ali et al. 2019)- as well as a better working capacity and purer concentration of CO2 produced compared to regular TCSD. TVSD would be the method to use, should we have chosen to use a solid sorbent, however we have chosen to use a liquid solvent for the sake of simplicity.

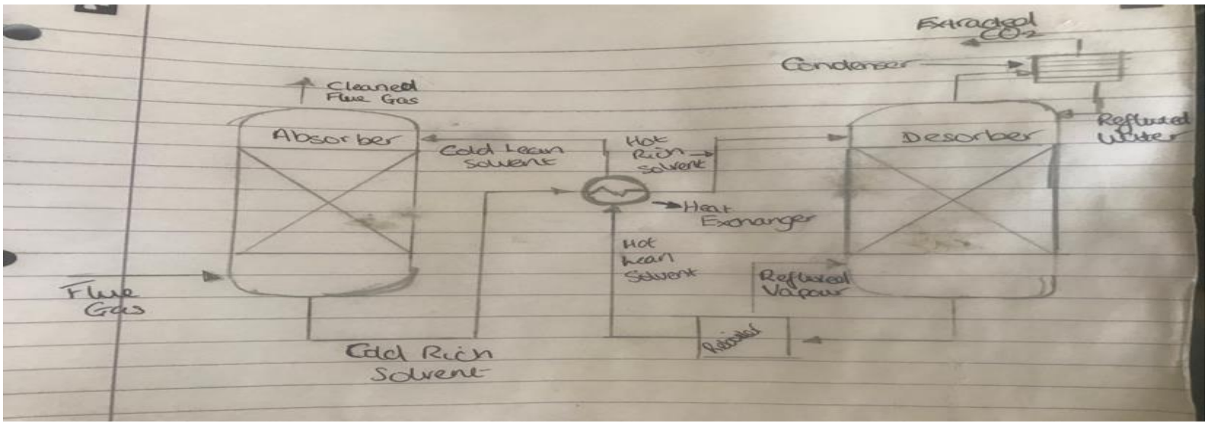


Figure B. *Basic schematic for a DAC, using MEA as a solvent for the absorption and desorption of CO2.*

The most used liquid solvent is MEA, an amine-based solvent. In this process the solvent is cycled through an absorber, heat exchanger and desorber and in the desorption section the carbamate formed during the absorption reactions is heated at temperatures just below 80 °C to release CO2 which is passed through a condenser and collected. Despite being widely used MEA must be regularly topped up due to the solvent experiencing degradation, while also being quite corrosive and requiring a lot of energy to regenerate. As such, Group 52 has decided to use a sodium hydroxide solvent as our sorbent, as it is far more readily available and does not require a high pressure for absorption to occur.

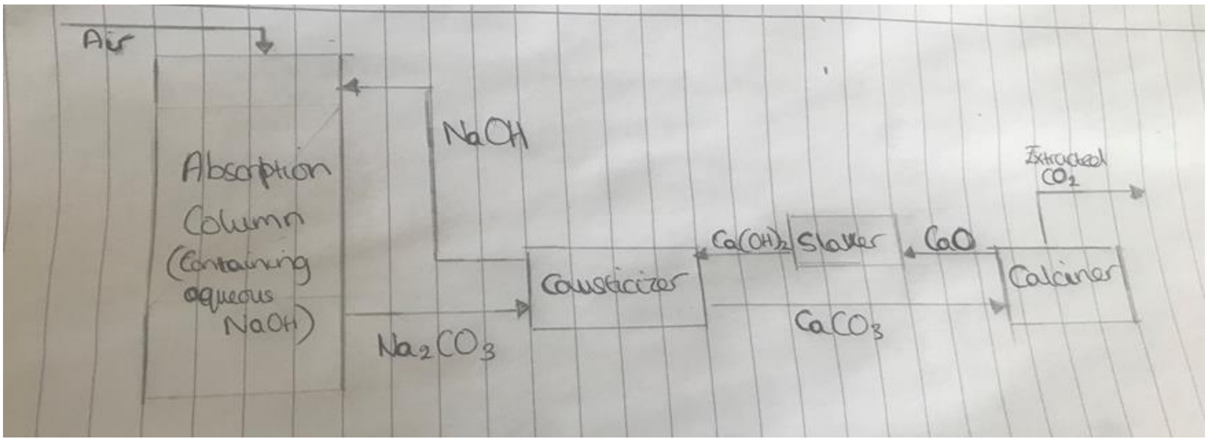


Figure C. *Schematic of the carbon capture process using sodium hydroxide as the solvent as well as how the solvent is regenerated.*

Consequently, our facility will not require a desorption or cooling tower, but the CO2 shall instead undergo disassociation through various reaction stages in the calciner and causticizer. (see Figure…) Sodium carbonate (produced once CO2 comes into contact with the solvent) is cycled out of the absorption tower into the causticizer where it becomes calcium carbonate. This calcium carbonate is the sent to a calciner where it is heated at around 900 °C to produce water vapour (steam), lime (calcium oxide) and CO2 (being of 35-50% purity), which is then siphoned off to be compressed for storage and other uses. The solvent is regenerated via the causticization process; the lime produced in the calciner is cycled to the slaker where it is hydrated to produce calcium hydroxide (slaked lime). This slaked lime is then passed into the causticizer where it is reacted with sodium carbonate to produce sodium hydroxide once more.

The carbon dioxide will be transported from the desorption section of the facility to the storage and reuse sections of the DAC facility. Carbon dioxide will be transported as a liquid in a pipeline with an internal diameter of 0.23148 m (from equation 1 [14]) at 20°C and 85 bars. The thickness of the pipeline is 0.00602 m (equation 2 [14]) giving the external diameter of 0.24622 m (equation 3 [14]). The pipeline will have a throughput of 5000 metric tonnes per annum. The liquid carbon dioxide input will be cooled to 20℃ through a water-cooling system [19] and transported 350 m to the reuse and storage sections of the facility. The condition of the carbon dioxide will be liquid at the output. Liquid transport was chosen as it is the safest [15] and most energy efficient over the short distance required to move the carbon dioxide [12]. The pipeline is made from high carbon steel to AISI 1030 [13] due to its high strength and toughness. The pipeline will not require any insulation [16] due to the short distance of the pipeline. Guadalajara is located in a valley with a largely flat terrain [18]; this is ideal for pipelining as there are no large changes in gradient so less pumps can be used. This means that the pipeline would only require two pumps; the first pump would be required to achieve the pressurisation of 85 bar in the pipeline. The second pump would be required to inject the carbon dioxide into the storage site. The total energy requirements for the transportation stage are 97.76 MJ per year as each individual pump would require 48.88MJ per year (equation 4 [15]).

1 main way of storing CO_2 is into oil, gas & water-bearing geological formations (this has already been done on a commercial scale as these areas are widely available and the technology for storage exists). This can lead to many benefits such as enhancing existing oil & gas reservoirs economically, and potentially locking CO_2 away completely. There are 4 main way of trapping CO_2: structural trapping (can lead to other forms of trapping), where an impermeable barrier or caprock blocks upward movement of CO_2 (see Figure D for 4 types of configurations); capillary trapping, where capillary forces prevent movement of CO_2 below low permeability on a small scale (see Figure E); solubility trapping (very low leakage risk as leakage occurs only if pressure significantly drops), where CO_2 dissolves into formation brine of a saline aquifer; mineral trapping, where CO_2 reacts with rocks containing Ca, Fe or Mg minerals, forming precipitation of carbonates in the pore space. CO_2 in supercritical form is injected into geological formations via injection wells (see Figure F). Structural trapping has the highest risk of CO_2 leakage and triggering seismicity, as compromised material can allow for CO_2 movement – this can be mitigated by intensive surveying before implementing injection wells, and injection wells need to have strong mechanical integrity for the casing, tubing or packer. Leaks can be monitored by performing SAPT, SAMT & RTS, temperature & noise logs, OAL, RTS & CBL. For reuse purposes, photobioreactors can be used to store CO_2 (see Figure G for some of the many types of photobioreactors, and have many pros & cons compared to each other), where they cultivate algae via photosynthesis in a closed system (to prevent external contamination & evaporation, and allows for more control such as determining optimal temperature, light, pH & algae concentration levels, and for mixing mechanisms) containing water, which receives CO_2, O_2, nutrients & sunlight, and excess algae can then be harvested & processed into algal oil.

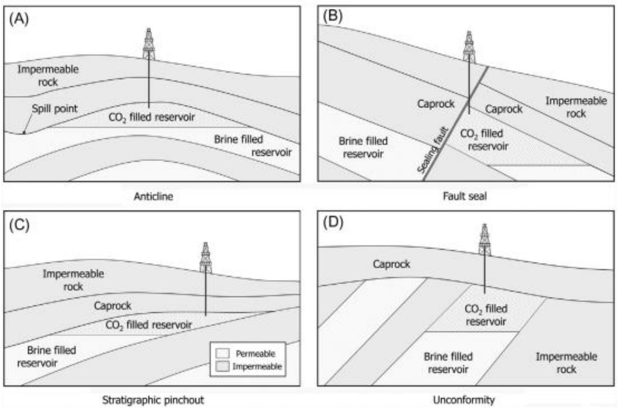


Figure D. *4 types of structural trap configurations (Rackley, S. A., 2017).*

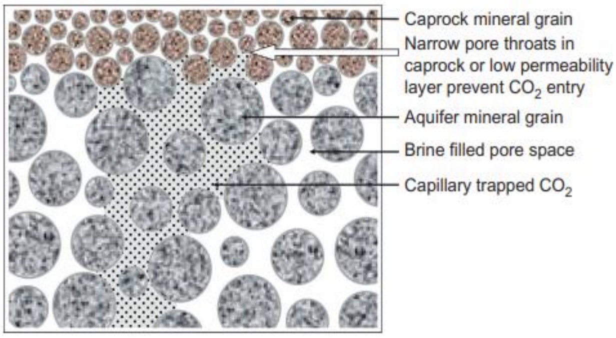


Figure E. *Capillary trapping mechanism (Rackley, S. A., 2017).*

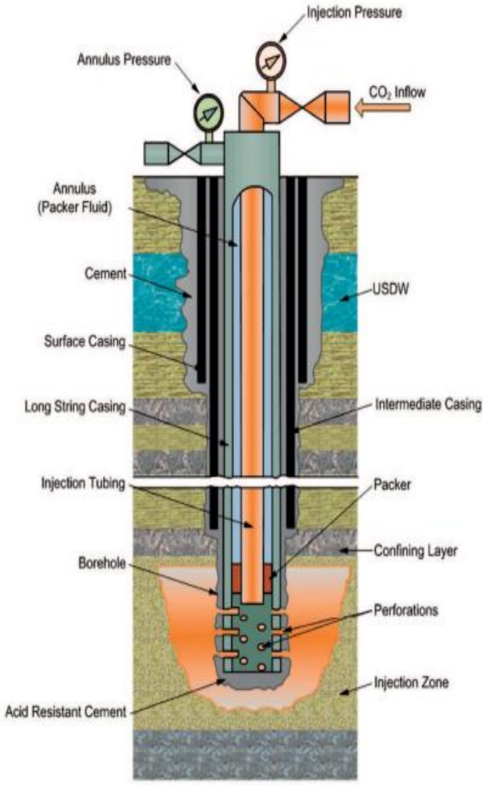


Figure F. *Schematic of an injection well (Gaurina-Međimurec, N. and Pasic, B., 2011).*

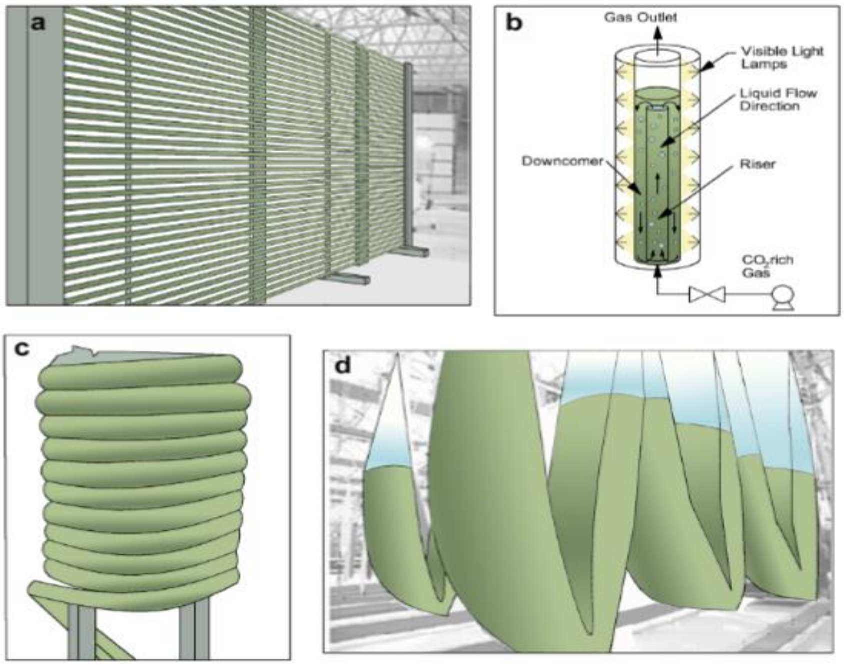


Figure G. *4 types of photobioreactors. From a – d: horizontal tubular; bubble column air-lift; helical-tubular; plastic bag, respectively. (Razzak, S.A., Hossain, M.M., Lucky, R.A., Bassi, A.S. and De Lasa, H., 2013).*

Research on reusing CO_2 delved into its uses currently and some into what could be achieved in the future. The main use for CO_2 currently is for flash freezing food, putting into carbonated beverages, to make building materials like cement, fire extinguishers, fuel and a few more. It was found that to make CO_2 back into fuel, 1.3-1.5 units of energy was needed to make 1 unit of energy [21]. Another pathway that was researched into was the use of an algae farm to store, reuse, and capture CO_2. Algae has been found to have numerous uses including as a biofuel and as a soybean replacement for food and feedstock. Using Algae as a food source would decrease crop greenhouse gas emission by 17% and could replace 26% of natural gas used to produce energy [22]. The algae farm that was in the research paper was able to produce an algae dry weight of 42.4 million kg per season. The conditions that the algae would need to be grown at are a pH of 7-9, water temperature of 20°C-30°C and would be able to intake 1.3kg-2.4kg of CO_2 per 1kg of algae [23]. This research led our group to decide to incorporate an algae farm with our DAC facility so that the CO_2 can be used to grow the algae that can then be processed and transported to the companies that process the algae into their own products. This would allow for a more versatile use reuse of CO_2 and would also decrease the amount of CO_2 put into the atmosphere, allowing for a faster decline in the amount of CO_2 left in the atmosphere. A vertical farm was considered as to reduce the amount of space the facility would take up.

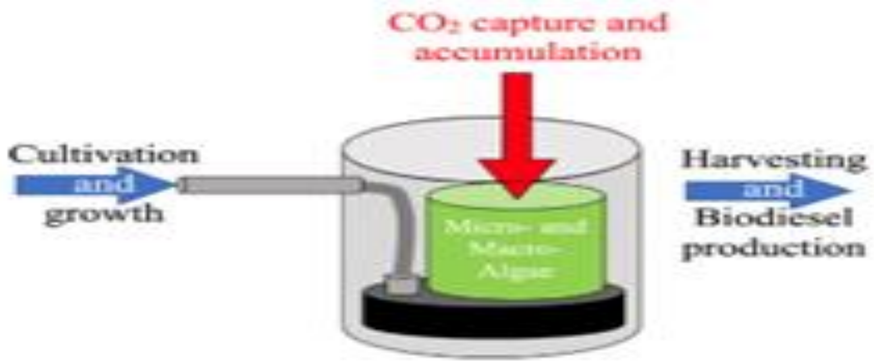
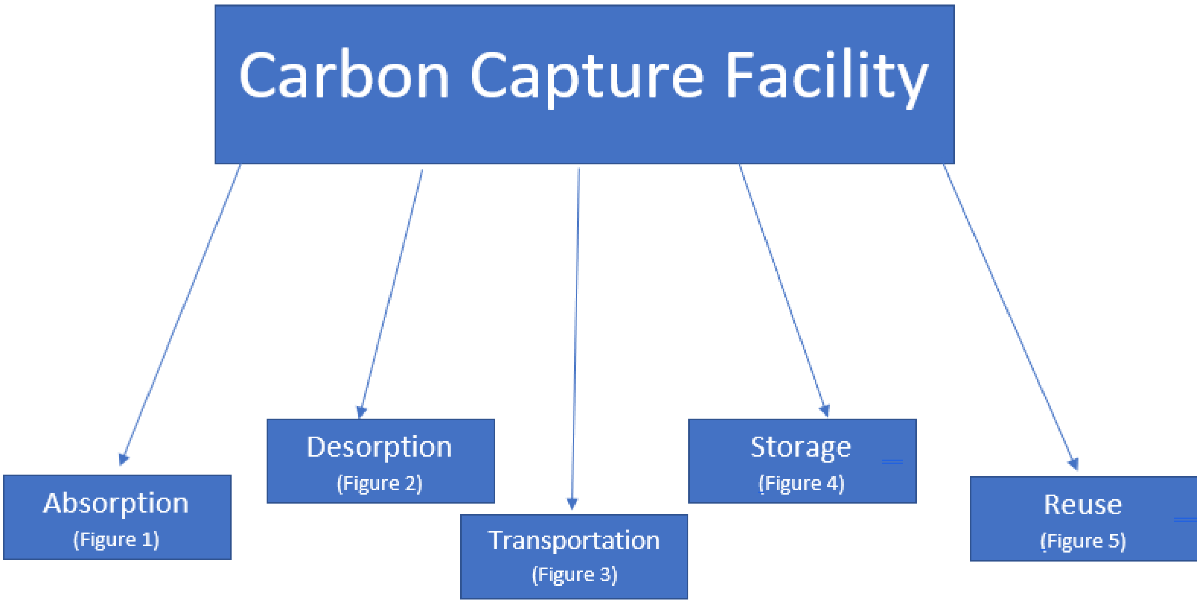


Figure H. *Graphical representation of algae farm process [23].*

Overall the purpose of this project was to create a concept design for a DAC facility with the goal of being carbon neutral. We took alternative energy sources into consideration such as wind and solar power to be the accessory supplies as those alone would not be sufficient enough to power our facility. In addition, if hydrogen power were to develop we could transform our current fossil fuel powered plant to further aid our carbon neutrality goal. We've calculated that our facility will require an estimated energy demand of 45GJ which is equal to 12500kWh.

REQUIREMENTS

Objective Tree



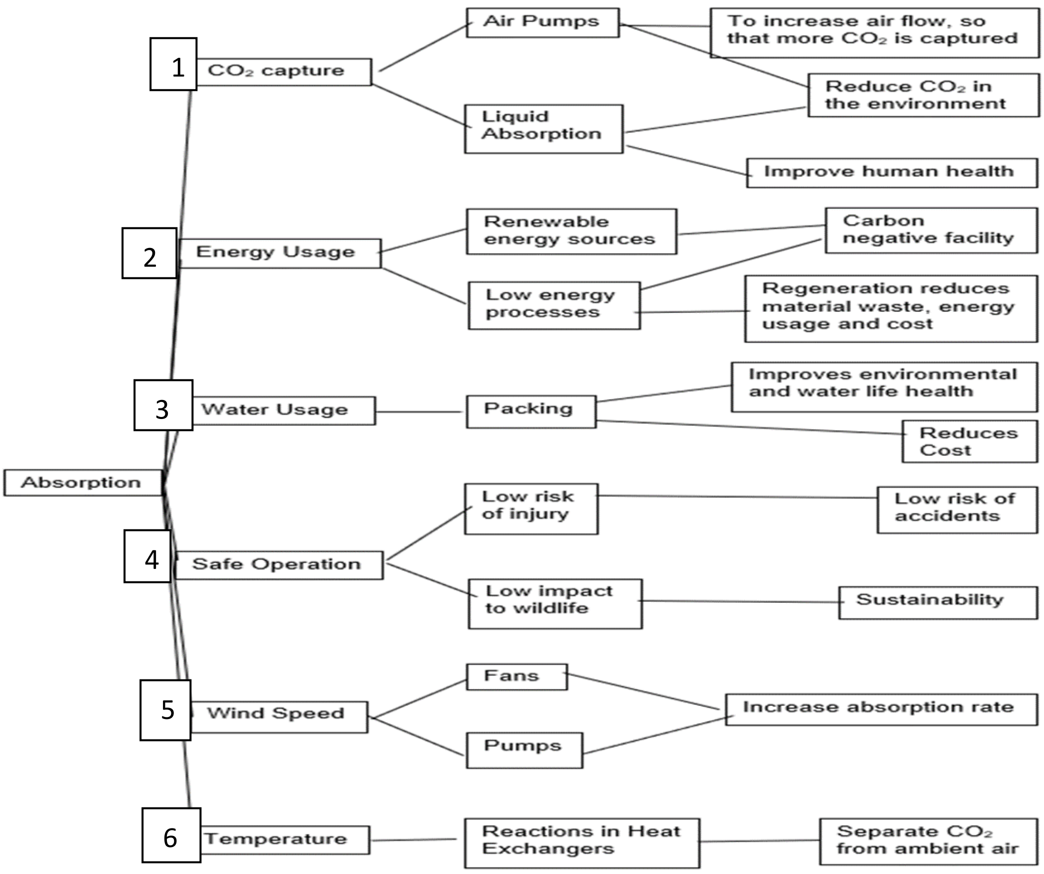


Figure 1. *Absorption objective tree analysis.*

Figure 2. *Desorption objective tree analysis.*

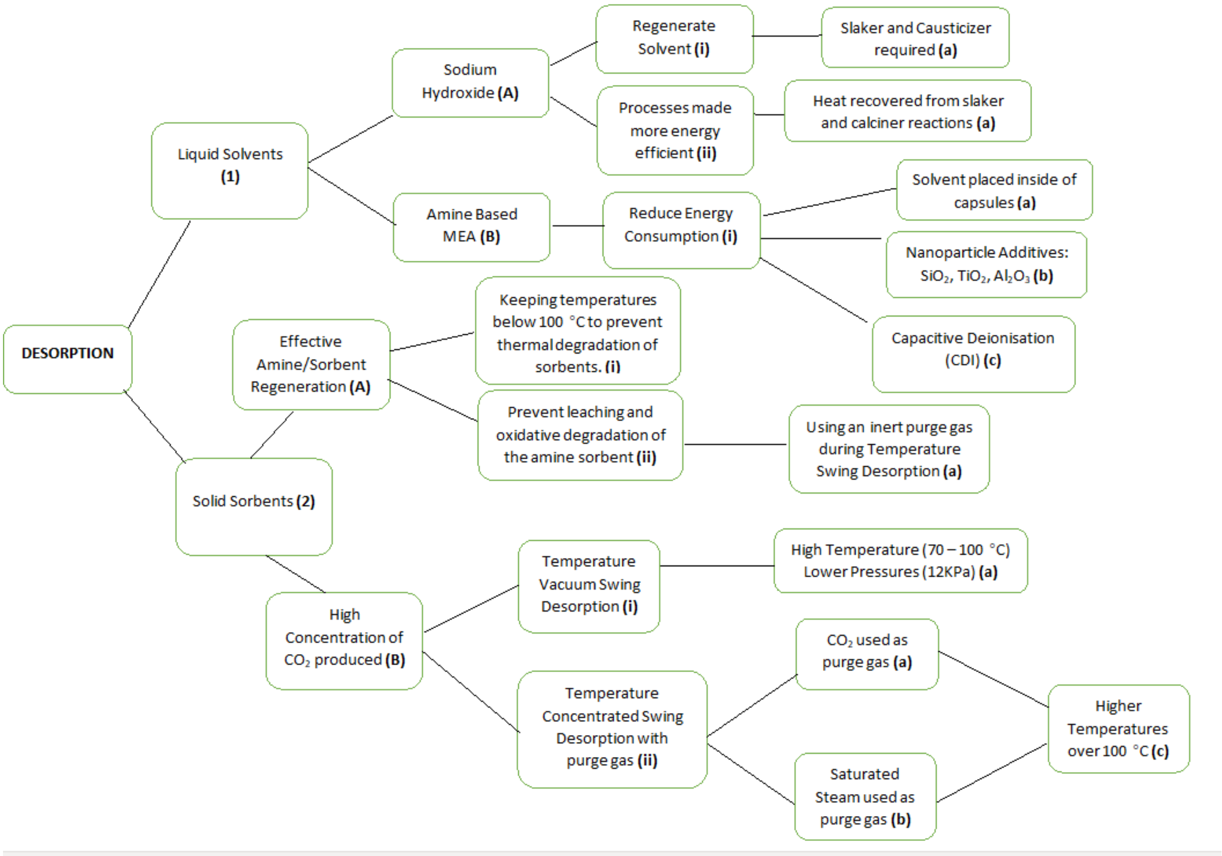
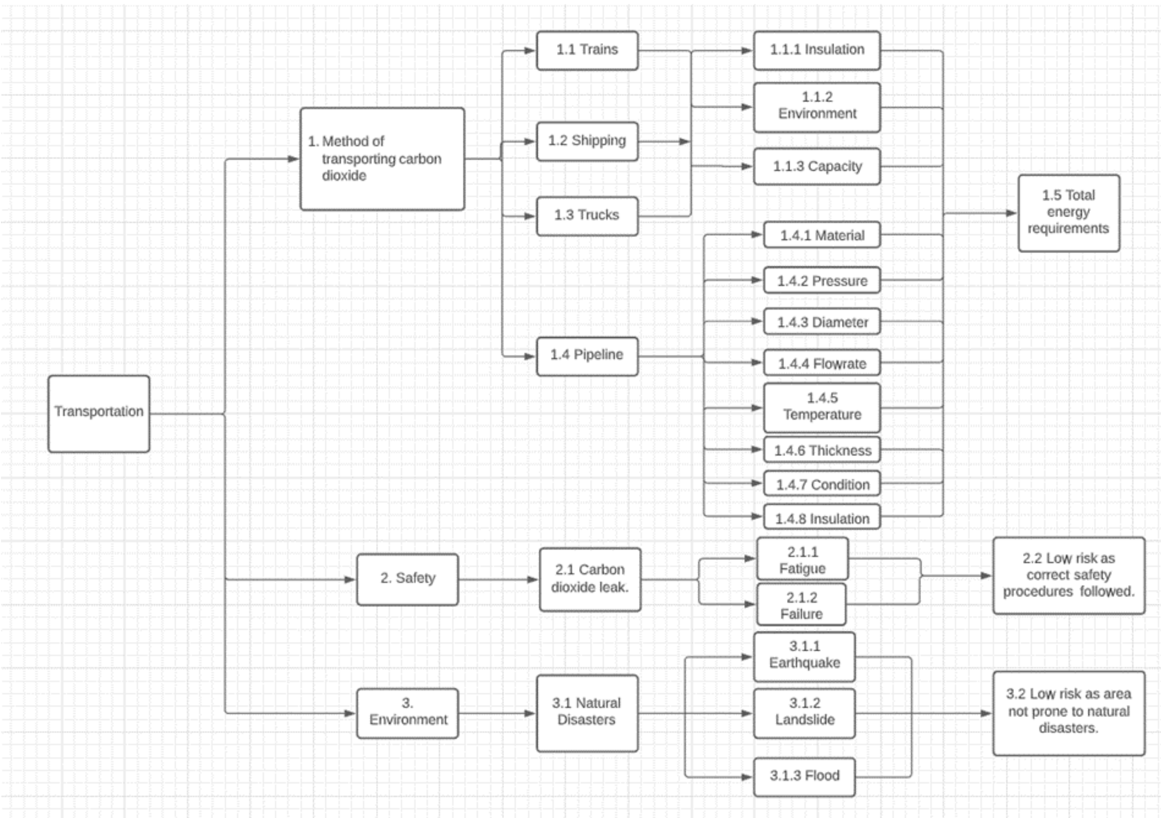


Figure 3. *Transportation objective tree analysis.*



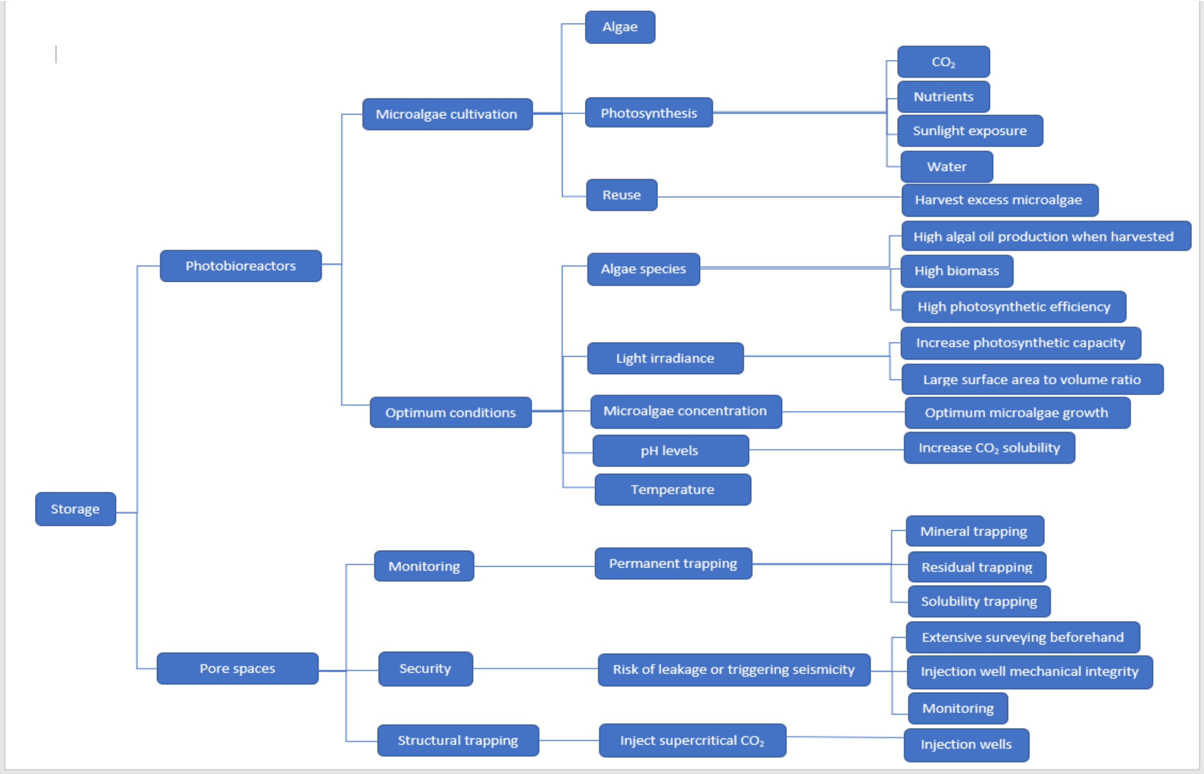


Figure 4. *Storage objective tree analysis.*

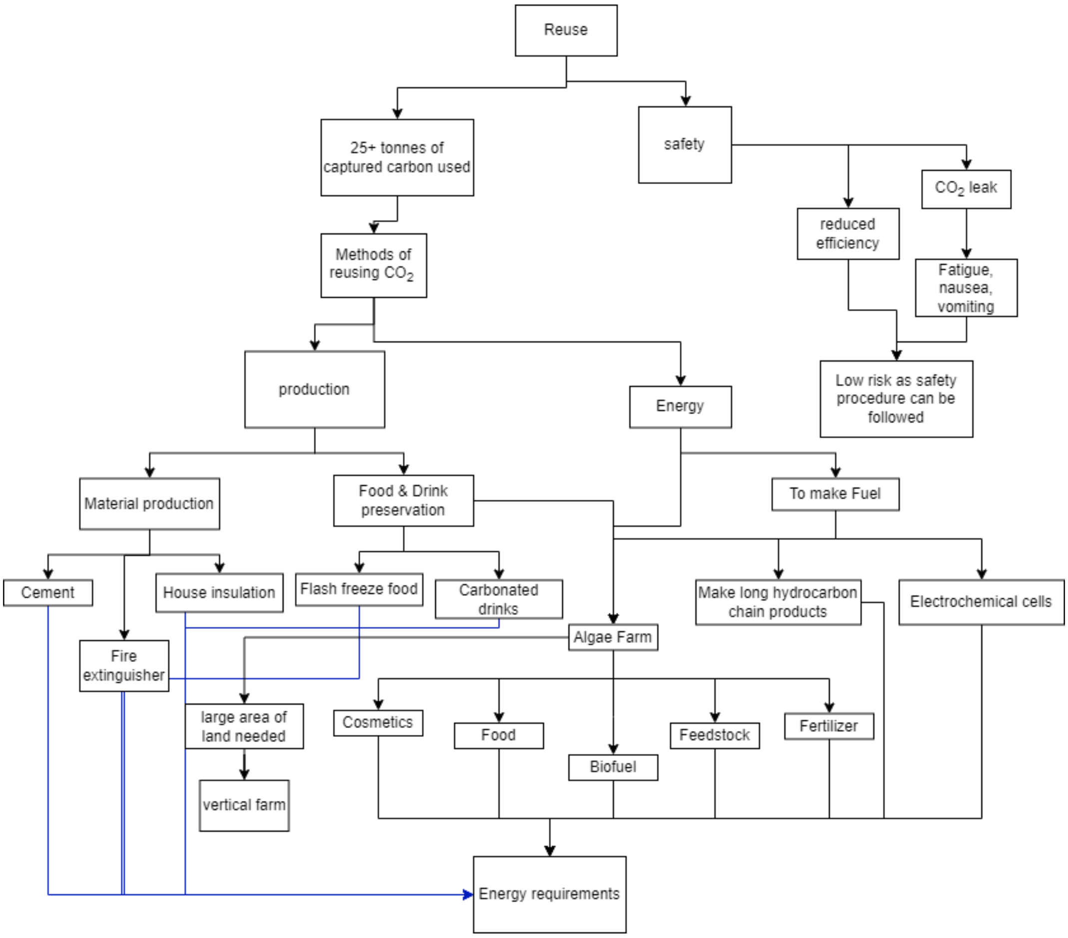


Figure 5. *Reuse objective tree analysis.*

Requirements Specification and Adequacy Assessment

<using the suppled high-level requirements document as a starting point and the work you have undertaken in the objective tree and functional analysis, refine and add detail to it along four key criteria or directives – functional, technical, customer, and quality. Wherever possible, requirements should be quantifiable and adequate i.e. meeting the 5 criteria: measurable, adequate i.e. complete, consistent, traceable, disambiguous and atomicity.>

System	Requirement number	Description	Requirement Type	Rationale	Traceability to objective tree
1. Air capture and CO2 absorption or adsorption	1.1	The Inputs will be ambient air and solvent, NaOH. Energy will also be an input. The outputs will be Na_2CO_3 and eventually CO_2.	Air Capture	The solvent is NaOH and when this reacts with ambient air it forms NA_2CO_3 and once desorbed CO_2 is formed. Energy is needed to power the pumps and the fans.	1,2
	1.2	The concentration of CO_2 in the air varies from 350ppm to 450ppm in Guadalajara.	Air Quality	The higher the concentration of CO_2 in the air the more CO_2 can be captured and the volumetric flow doesn't need to be as high.	1,2,5
	1.3	The volumetric flow rate of the air needs to be around 33,000 m^3/h.	Wind Speed	This is the required air speed to ensure that 570kg of CO_2 is absorbed every hour.	1,5
	1.4	The current capture fraction from air is 50% but could easily be increased to 62.5% with	Air Capture	This determines how much CO_2 can be absorbed based on the air quality.	1

		small developments			
	1.5	There will be 72 fans and blowers to take in air and then there will be a pump to pump the solvent around each absorber tower.	Air Capture	These parts consume high amounts of energy but ensure that CO_2 is absorbed efficiently. These also need to be made safe so that they can be repaired without injury to workers.	1,2,4
	1.6	The plant will be operational 24/7.	Air Capture	This ensures that enough CO_2 is absorbed but increases energy consumption and water usage.	1,2,3
	1.7	The plant will use around 13,000MWh to absorb 5000 tonnes of CO_2.	Energy	This energy value needs to be produced by the solar panels and the power plant to ensure that the plant can operate at full capacity.	2
	1.8	We are using liquid sodium hydroxide as our solvent.	Air Capture	This solvent reacts with the CO_2 in the air, in an absorber tower, to form Na_2CO_3. This solvent doesn't need to be excessively heated to	1,6

				absorb the CO_2.	
	1.9	We are using honeycomb structured packing in our absorber tower.	Air Capture	This increases surface area and spreads the solvent into a thin film which improves performance. This process does involve water loss but is reduced by the use of packing.	1,3
	1.10	571kg of CO_2 will be removed from the air per hour.	Air Capture	This requires a wind speed of 33,000m^3/h and 200ppm of CO_2 to be absorbed from the air.	1,3
	1.11	The blower needs to be large enough to take in 571kg of CO_2 and hour at a rate of 33,000m^3/h. An example fan has a fan power of 17.2kW and 72.1% efficiency. The fan will be under 2m in diameter.	Wind Speed	The blower is vital in ensuring that the air flow is high enough to take in enough air so that 5000 tonnes of CO_2 of air can be absorbed. They also use a lot of energy as there will be 36 of these in each tower (72 in total).	1,2,5
2. CO2 Desorption	2.1	Carbon dioxide mixture produced with a purity of at least 15%.	Functional/ Technical: CO_2 Stripping	The algae only requires a CO_2 concentration of 1 -2%. However, having a higher carbon dioxide	2B

				concentration is advantageous as this means there will be more uses for it.	
	2.2	Causticizer and calciner required for CO_2 stripping.	Functional/ Technical: CO_2 Stripping	Causticizer converts sodium carbonate into calcium carbonate which can be decomposed in the calciner, producing CO_2.	1A.ai
	2.3	Temperatures of 800–1000°C required in the calciner.	Functional: Temperature Requirements	Decomposition reaction in the calciner requires a large amount of energy to break down the calcium carbonate into calcium oxide and CO_2.	2B.iic
	2.4	Slaker and calciner required for solvent regeneration	Functional/ Technical: Solvent Regeneration	Slaker hydrates the lime produced in the calciner allowing it be reacted with sodium carbonate in the causticizer to produce NaOH once more.	1A.ai
	2.5	Around 75%-85% of the solvent should be regenerated.	Functional/ Technical: Solvent Regeneration	Not all the solvent will be regenerated as some of it will be lost in	1A.i

				the intermediate processes and products. However solvent regeneration is essential in order to keep costs down so that wholly new solvent is not needed for each cycle.	
	2.6	13,000 MWH total energy required for the absorption, carbon stripping and regeneration processes	Functional/ Technical: Energy Requirement	Decomposition reaction within the calciner is extremely energy intensive as well as the causticization processes.	
	2.7	Calciner, causticizer and slaker can be operated 24/7.	Functional: Operation Time	With the exception of down time for maintenance / check ups on the machines, should be able to operate 24/7 as they do not require constant manual inputs to replace reactants and products.	
3. CO2 Transportation	3.1	The condition of the CO2 will be liquid at the input and outputs.	Transport	Most energy efficient and safest option for the short transportation distance	1.4.7

	3.2	Throughput of the pipeline will be 5000 metric tonnes per annum.	Transport	DAC facility designed to capture 5000 metric tonnes per annum.	1.4
	3.3	Pumping stations required.	Pressure	Two pumps will be required to achieve the pressurisation in the pipeline and to inject the CO_2 into the storage site.	1.4.2
	3.4	Pipeline pressure of 85 bar.	Pressure	Pressure requirement to keep the CO_2 in liquid phase.	1.4.2
	3.5	Pipeline diameter – 0.25 m and thickness – 0.006 m.	Pipe size	Calculated by equations researched to ensure throughput requirements can be met.	1.4.3 1.4.6
	3.6	Use of tanker trucks, trains and ships.	Transport	Not required as the storage and recycling facilities are adjacent.	1.4
	3.7	Refrigeration conditions	Cooling System	A cooling system would be required to reduce the temperature to 20℃.	1.4.5
	3.8	Energy requirements – 97.76 MJ per year.	Energy	Energy required by two pumps to transport 5000 metric tonnes of CO_2 per year.	1.5
4.CO2 storage	4.1	Use the microalgae species ‘Scenedesmus opolienis’	Functionality	This microalgal species had the most vigorous growth rate,	‘Algae’ from ‘microalgae cultivation’

				higher photosynthetic efficiency, larger biomass & algal oil production.	
	4.2	Use flat panel photobioreactor design	Functionality	Provide quality conditions for algae to undergo photosynthesis and grow.	'Large surface area to volume ratio' from 'Light irradiance'
	4.3	Perform SAPT, SAMT & RTS, temperature & noise logs, OAL, RTS & CBL	Maintenance	Need to monitor injection wells as they're the most likely route for CO_2 leakage.	'Injection well mechanical integrity' from 'Risk of leakage or triggering seismicity'
	4.4	Photobioreactor design to have 2000L capacity minimum	Functionality	Water needed for algae cultivation, and capacity large enough for commercial scale.	'Water' from 'Photosynthesis'
5. CO2 reuse	5.1	The DAC facility shall be capable of using at 25 tonnes of the captured carbon to make a new product.	Functional	A big part of decreasing our carbon footprint would be to reuse the captured carbon to reduce the amount we put back into the atmosphere. In the future, as technology advances, the reuse capacity can be increased so that all	5. CO2 reuse

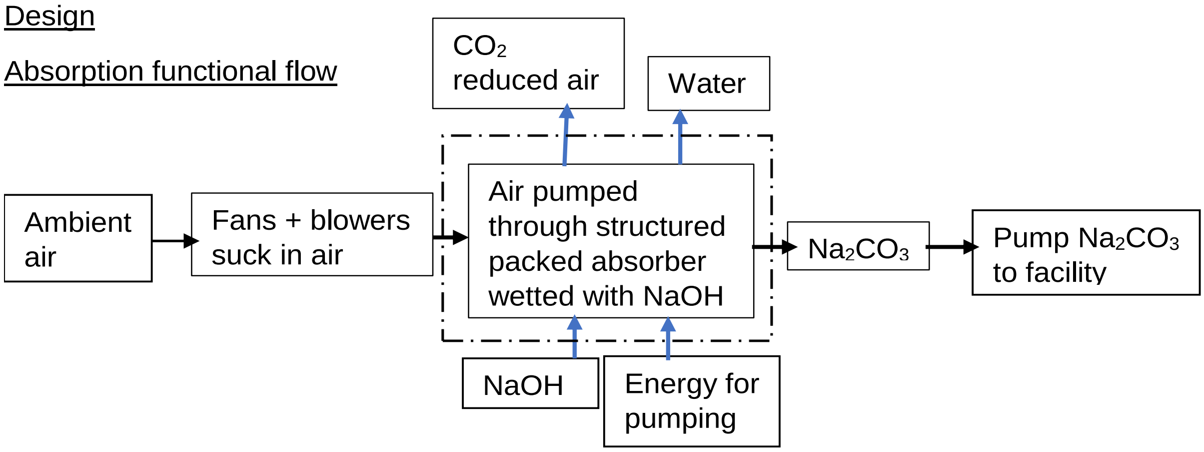
				captured carbon is used.	
	5.2	The DAC shall use an Algae farm to reuse the CO_2	Functional	An algae farm allows us to not only reuse the CO_2, but allows for storage and the production of usable products that will lessen our impact on the environment further.	

CONCEPT DESIGN

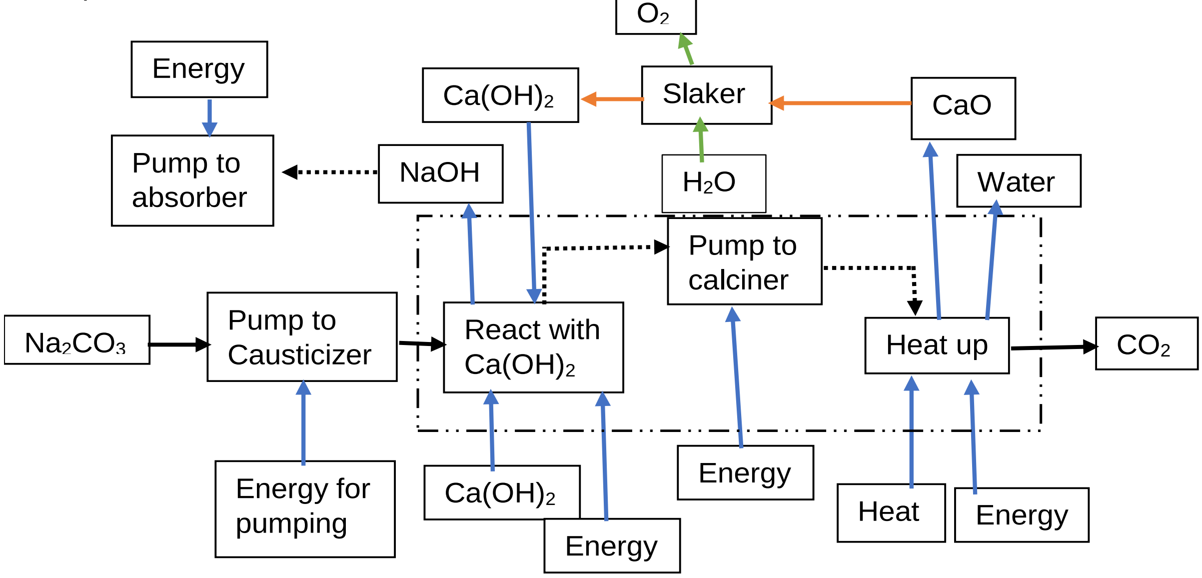
Functional Analysis

<u>Design</u>

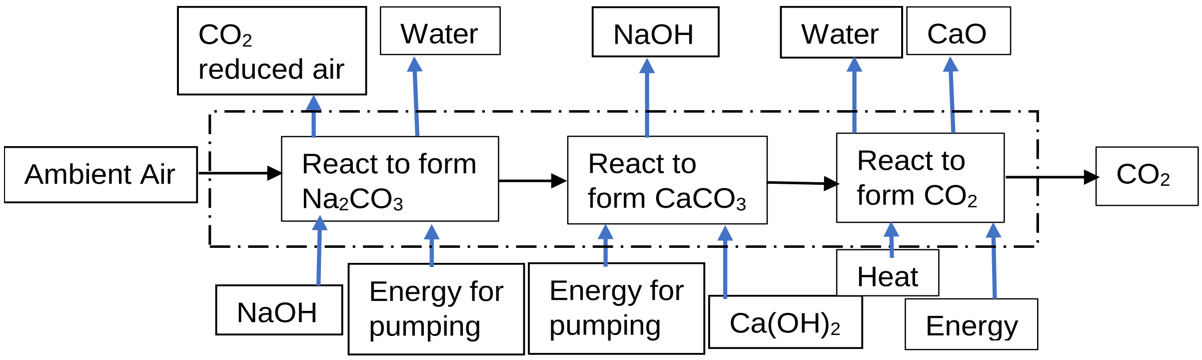
<u>Absorption functional flow</u>



<u>Desorption functional flow</u>



<u>Overall facility</u>



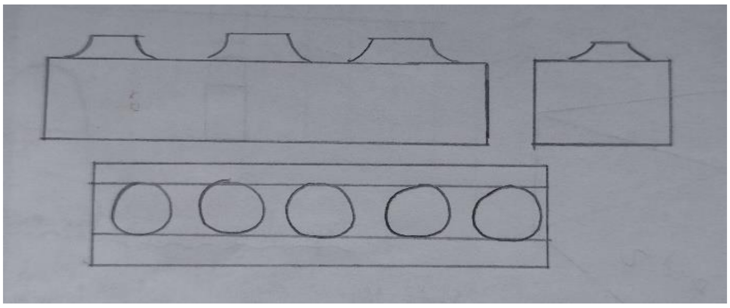
Inputs and Outputs → Material Flow — · — System Boundary

Secondary Process Material Flow → Secondary Process Inputs and Outputs

Design Ideas

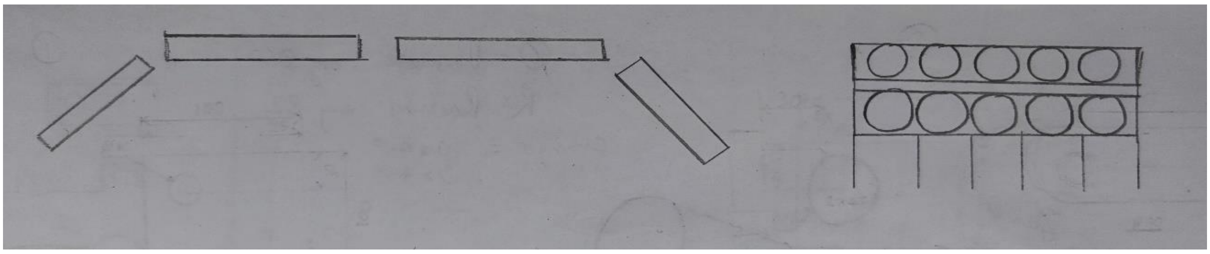
Brainstorming – initial concepts

Sketch 1:



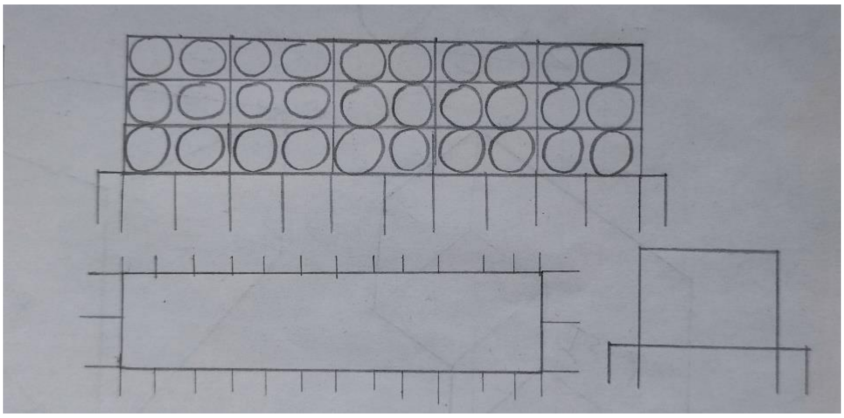
This first design uses large singular fans that are mounted onto the roof of the facility where all the absorption and desorption processes occur. These fans may not be enough to draw in all the air needed to reach the target of 5000 tonnes of CO_2 a year.

Sketch 2:



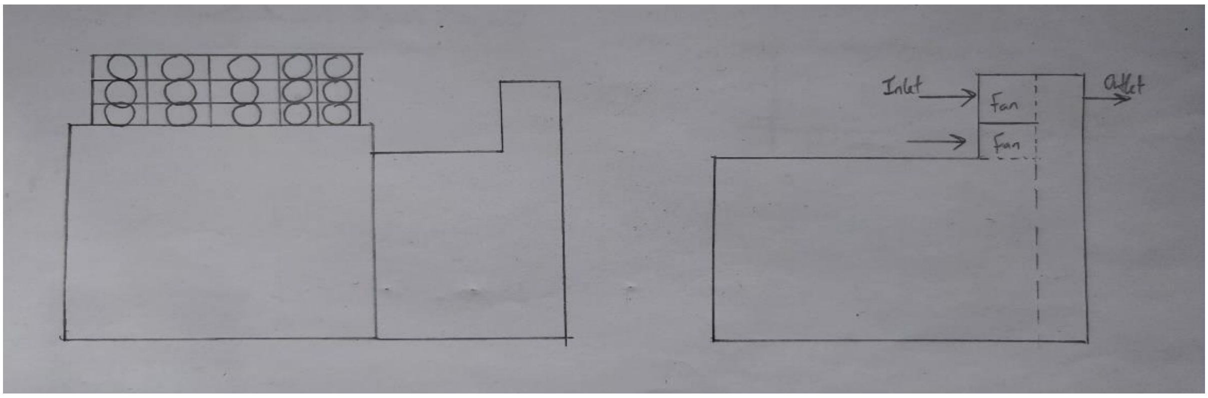
This second design uses smaller fans rather than the larger ones above and these are arranged into racks of fans, 1 fan tall, then 2 of these racks are put together. 4 of these towers are then arranged into the shape on the left so that even if the wind direction changes some of the fans can still operate at their full potential. This would allow for the most amount of air to be taken in by the DAC facility.

Sketch 3:



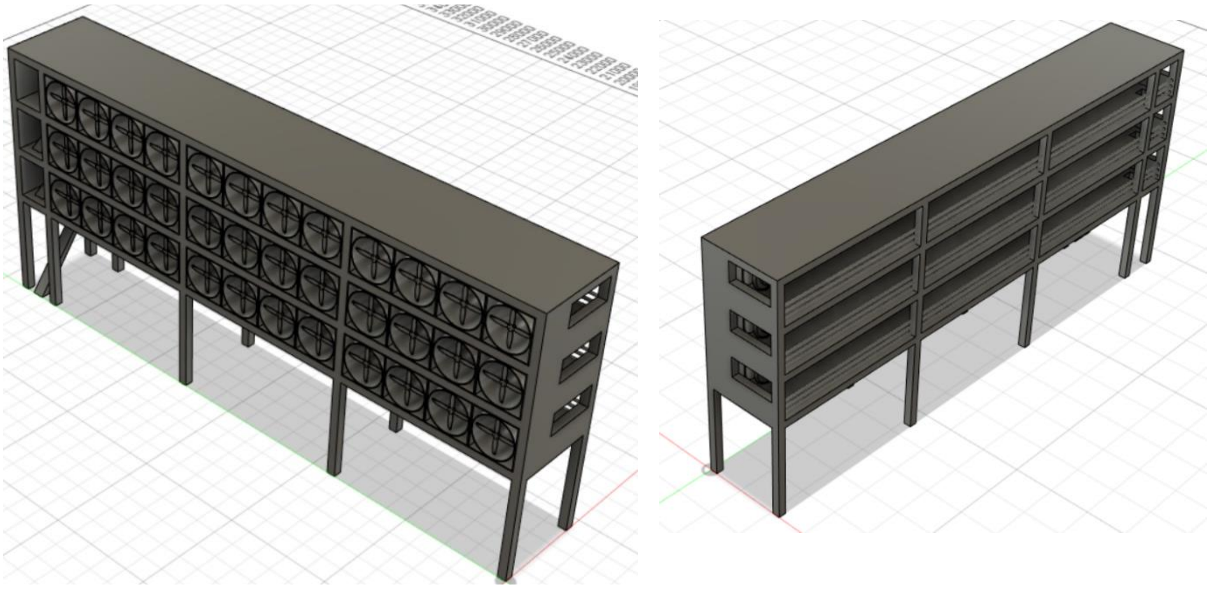
This third sketch still uses small fans, but the tower is significantly bigger. This tower is standalone and so would need to be connected to a building where the absorption and desorption processes would take place. This would allow for maximum intake from that area, increasing the efficiency of the DAC overall.

Sketch 4:



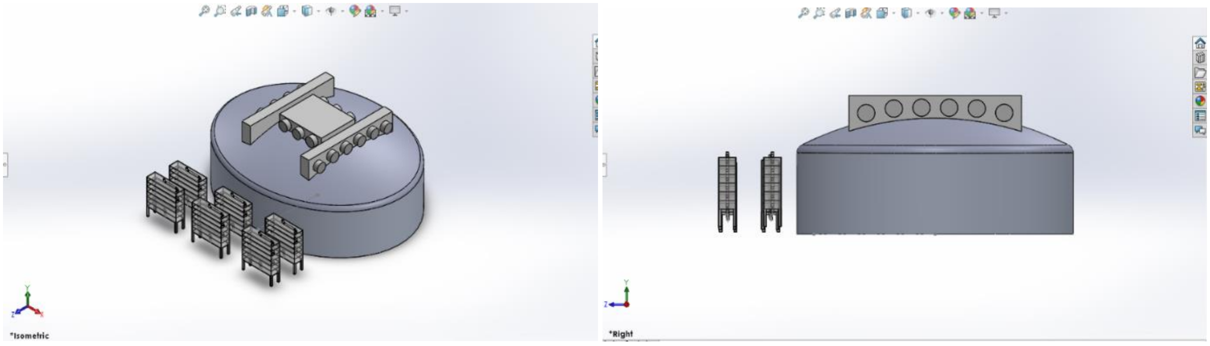
This fourth sketch uses a fan arrangement like that of the third sketch however rather than the fans being arranged in a standalone tower, the tower is placed on top of a building. This building can then be used to carry out the absorption and desorption processes. The advantage of this sort of design over the third design is that it requires less exposed piping that could get damaged and increases the cost. However, the downside of this design is that the building design restricts the size, shape, and placement of the fan tower and this could negatively affect its performance.

Sketch 5:



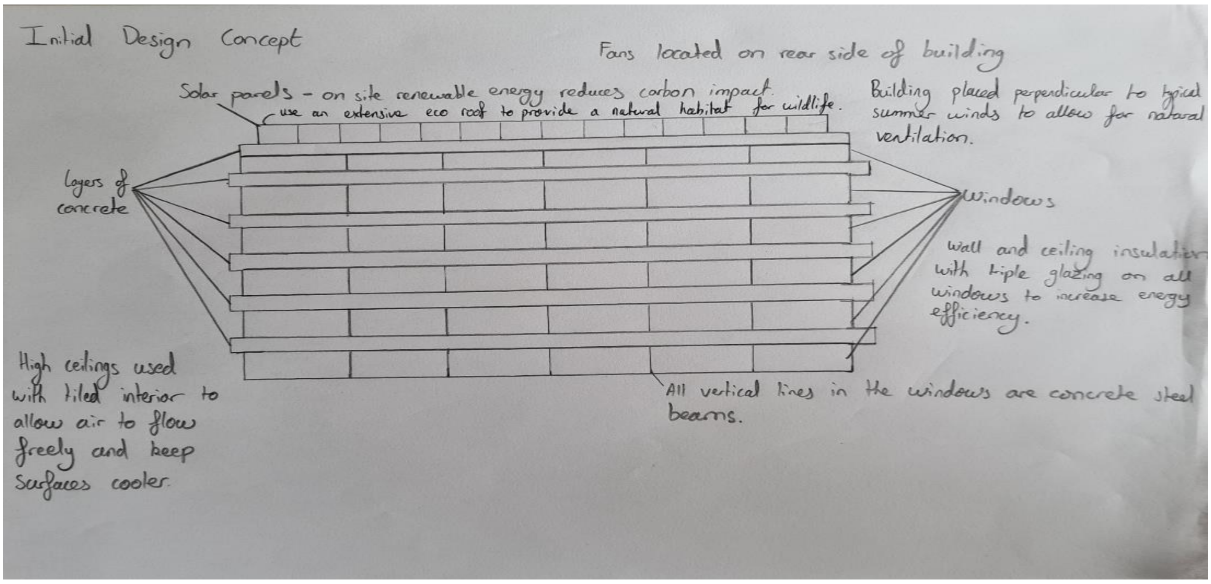
This is a CAD design for the standalone tower of fans from sketch 3. In this design the legs are kept within the outline of the tower rather than being wider than the rest of the tower. Also, this tower still uses small fans but there are 36 fans rather than 30 from sketch 3. This CAD design is also more developed than the initial sketch. It has rails around the back which makes it safer for maintenance workers to walk around at that height. It also has stairs so that workers can easily get to all of the fans in case of maintenance.

Sketch 6:



This CAD design is an initial design for a potential layout of the DAC facility. It has absorber fans on the roof of the oval building. The absorption and desorption processes would then be undertaken inside this building. The external feature on the left of the building is a vertical algae farm. This would be used so that some of the CO_2 could reused rather than being stored underground. A disadvantage of this design is that the amount and the size of the fans are restricted by the building size and shape and so this could restrict the capacity of the building. This would lead to little CO_2 being taken in and as a result, the goal of processing 5000 tonnes of carbon dioxide would not be reached. Also, this design would be putting the roof under a large and constant load which would mean that stronger and potentially more expensive materials would have to be used, increasing the overall costs for building and any repairs that are needed.

Sketch 7:

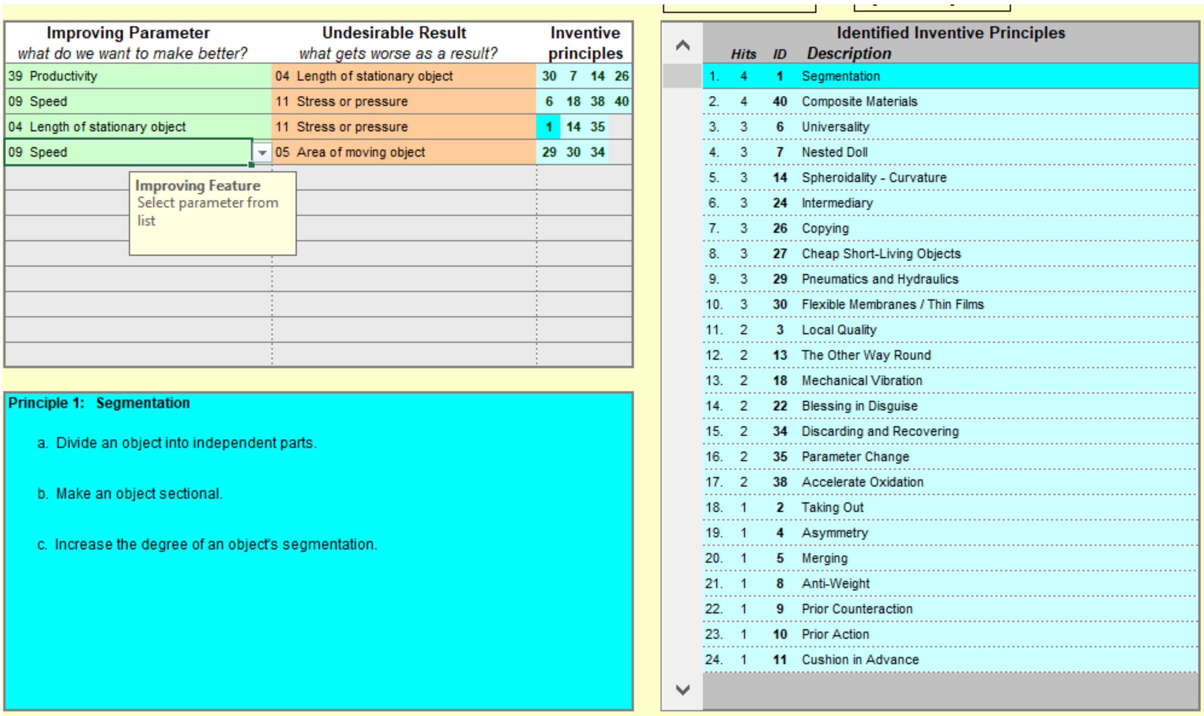


Initial design concept sketch to show a potential building design for the DAC facility with consideration to reduce the environmental impact. Large windows were used for the design to allow for natural lighting reducing the energy requirements for artificial lighting. The building was designed to be perpendicular to typical summer winds to allow for natural ventilation in combination with high ceilings and a tiled interior allowing for air flow freely and cool the facility. Solar panels were utilised to give on site renewable energy with an eco-roof which provides natural insulation reducing energy costs.

Morphological Chart

DAC facility components	Solution	1	2	3
Absorption		Liquid	Solid	Amine
Fan Size		Small	Large	
Fan Arrangement		Single rack	Multiple stacked racks	Roof mounted
Power		Solar	Wind	Power Plant
Reuse		Algae farm	Compressed tanks to be sold	Fuel
Storage		Geological Storage	Offshore sea storage	On-site Tanks

TRIZ Contradiction Matrix



Improving Parameter *what do we want to make better?*	Undesirable Result *what gets worse as a result?*	Inventive principles
39 Productivity	04 Length of stationary object	30 7 14 26
09 Speed	11 Stress or pressure	6 18 38 40
04 Length of stationary object	11 Stress or pressure	1 14 35
09 Speed	05 Area of moving object	29 30 34

Improving Feature
Select parameter from list

Principle 1: Segmentation

a. Divide an object into independent parts.

b. Make an object sectional.

c. Increase the degree of an object's segmentation.

Identified Inventive Principles

	Hits	ID	Description
1.	4	1	Segmentation
2.	4	40	Composite Materials
3.	3	6	Universality
4.	3	7	Nested Doll
5.	3	14	Spheroidality - Curvature
6.	3	24	Intermediary
7.	3	26	Copying
8.	3	27	Cheap Short-Living Objects
9.	3	29	Pneumatics and Hydraulics
10.	3	30	Flexible Membranes / Thin Films
11.	2	3	Local Quality
12.	2	13	The Other Way Round
13.	2	18	Mechanical Vibration
14.	2	22	Blessing in Disguise
15.	2	34	Discarding and Recovering
16.	2	35	Parameter Change
17.	2	38	Accelerate Oxidation
18.	1	2	Taking Out
19.	1	4	Asymmetry
20.	1	5	Merging
21.	1	8	Anti-Weight
22.	1	9	Prior Counteraction
23.	1	10	Prior Action
24.	1	11	Cushion in Advance

For our initial design, we wanted a single row of fans, however, this would take up too much room. Using the TRIZ matrix, we decided to segment the single row of fans and stack them on top of each other to allow for the same amount of coverage without taking up too much space. Another improvement we made was to the pipes. We wanted to increase the speed at which the CO_2 was transported at but this increased the stresses and pressure on the pipe, which could lead to leaks and bursts if it gets too high. The TRIZ matrix suggested that we used a composite material so that the pipes are strong enough to handle the stresses and pressure from the CO_2.

Final Design

Design Rationale

We have fans on the east and the west of the facility because the wind in Guadalajara comes from each of these directions for about 6 months of the year and this ensures that the facility operates at maximum capacity. We are using solar power to power the facility, but current energy estimates and technology would suggest that we also need a separate power plant to power the facility as solar power alone is not sufficient. This powerplant could use any fuel currently available such as fossil fuels but also hydrogen and biofuels, but can be replaced with technological advances.

Design Schematic

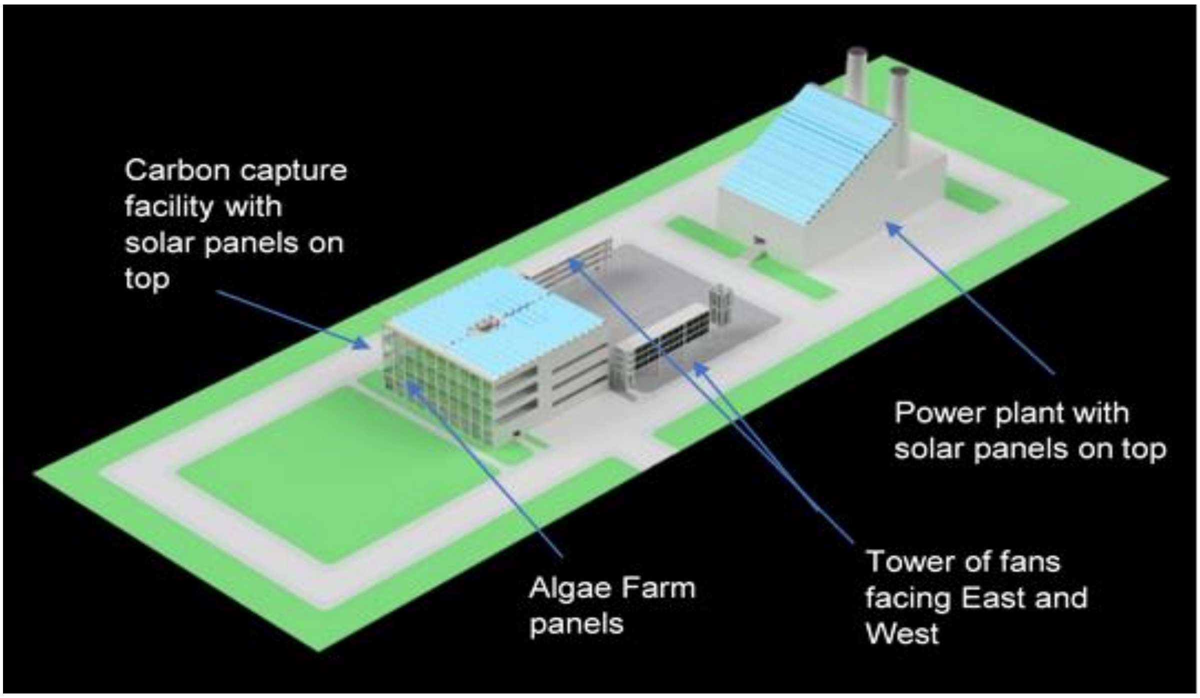


Figure 6. *Isometric view of the entire DAC facility*

This design uses 2 standalone fan towers one on the east of the facility and the other on the west of the facility. This is because the wind direction in Guadalajara isn't constant. For 6 months of the year the wind comes predominantly from the east and then for the other 6 months the wind comes from the west. So, by arranging the fans in this way ensures that the facility is always operating near to or at capacity throughout the year. Next to each of the fan towers are some absorber towers. Inside the absorber tower there is honeycomb shaped structured packing that is wetted by NaOH. Then CO_2 reduced air is released from the top of these towers and the Na_2CO_3 formed is removed from the bottom and pumped to the building on the left of the fans. This building is where the desorption processes take place. Once the CO_2 has been desorbed some of it is absorbed by an algae farm at the south of the building. The algae farm is designed to absorb this CO_2 so that it can be reused. The excess CO_2 is then piped from the facility to an underground storage facility. The algae farm and the solar panels face the south of the facility as this is where the sun predominantly comes from in Guadalajara.

The building on the right of the image is a power plant. The energy consumption of the facility is high and so current solar technology wouldn't be sufficient to power the facility on its own. So, without knowing how solar power will develop in the future or how significantly the energy consumption of DAC technology will decrease we have opted to include a power plant in our design. This power plant could be a traditional natural gas or coal plant with carbon capture to remove some of the CO_2 from the flue gases released to ensure the facility is still carbon negative. However, if a newer technology such as hydrogen power is developed the power plant could be changed to use this as its power source as it is a renewable source of energy and increases how carbon negative the facility is. If solar panel technology increases as well, we could power the entire facility with only solar power, as currently the efficiency of solar panels is around 20%.

The carbon processing building also has panels of algae photobioreactors facing the south side to obtain the most amount of sunlight. The algae can then be harvested and processed to be turned into a range of products. The algae can be dried in the facility, then transported to manufactures who use it in their products.

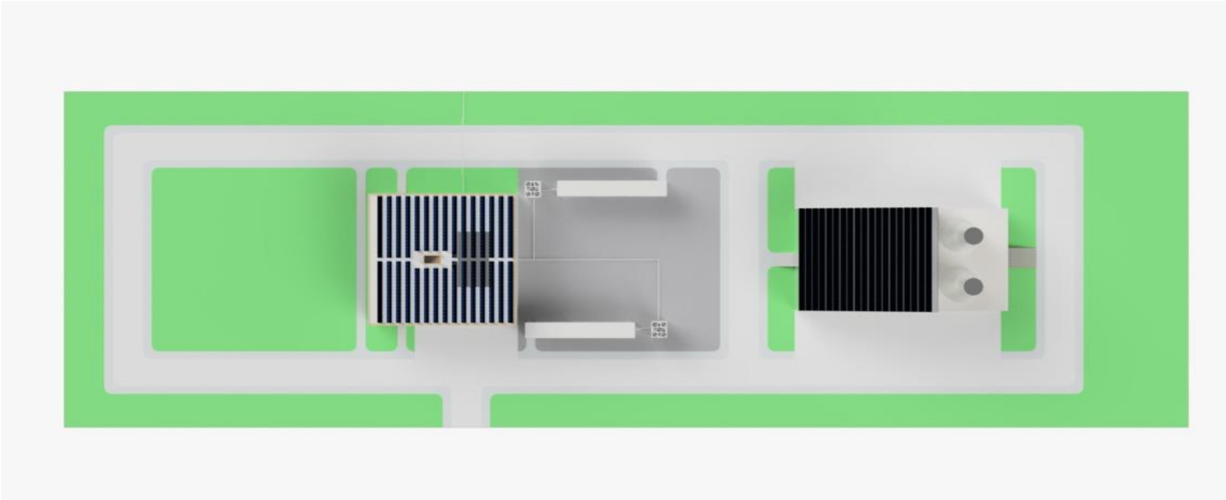


Figure 7. *Top view of the entire DAC facility*

The above diagram shows what the empty spaces of the 3 hectares will be used for. The red lines are roads and parking spaces. The green lines represent grass which helps to promote nature and is aesthetically pleasing.

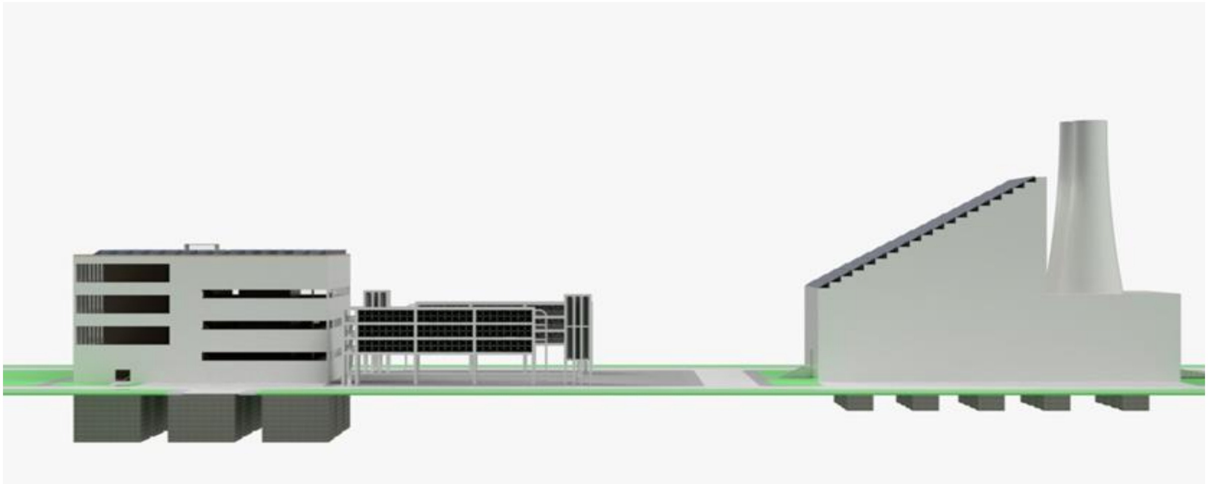


Figure 8. *Side view of the entire DAC facility*

Figure 7 shows the side view and shows the foundations of the buildings. The foundation for the buildings is made up of flexible pads that separate the foundation from the ground. This allows for the ground to move without the building moving to avoid any damage that could be caused due to earthquake. We would also place this facility as high up as we can and have raised entrances to the buildings to reduce possible risks caused by flooding in the area.

Figure 9. *close up of fan towers and carbon processing*

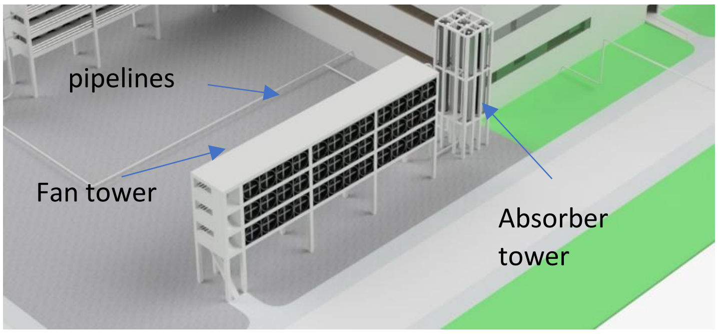


Figure 10. *close up of fans and absorber towers*

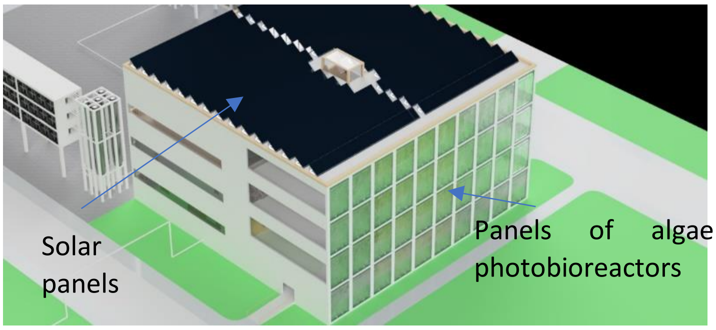


Figure 11. *close up of carbon processing facility*

The fan towers would hold 36 fans each with 12 fans horizontally and 3 fans vertically. This configuration allows for maximum air capture in that area. Figure 11 shows the kind of fans that we would use in each unit. With the other fan tower facing the opposite direction, this would allow us to capture the most air and therefore would be able to process more CO_2. The solar panels are angled at 35 degrees to allow for maximum sunlight to reach them. The pipes from the fan units to the processing unit would be made out of stainless steel as the chemical transported by the pipes is $CaCO_3$ which can increase corrosion rates in aluminium alloys and carbon steels.

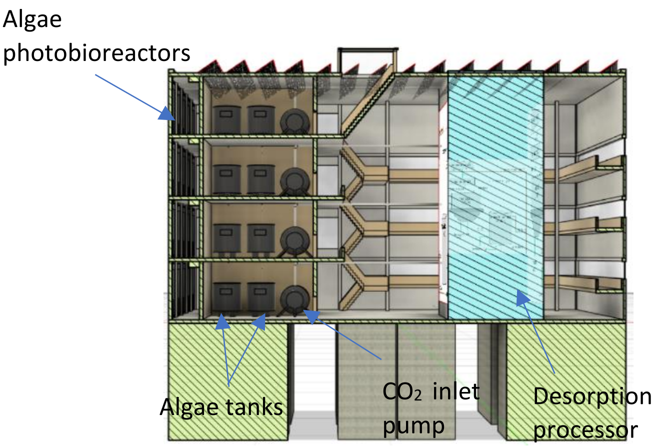


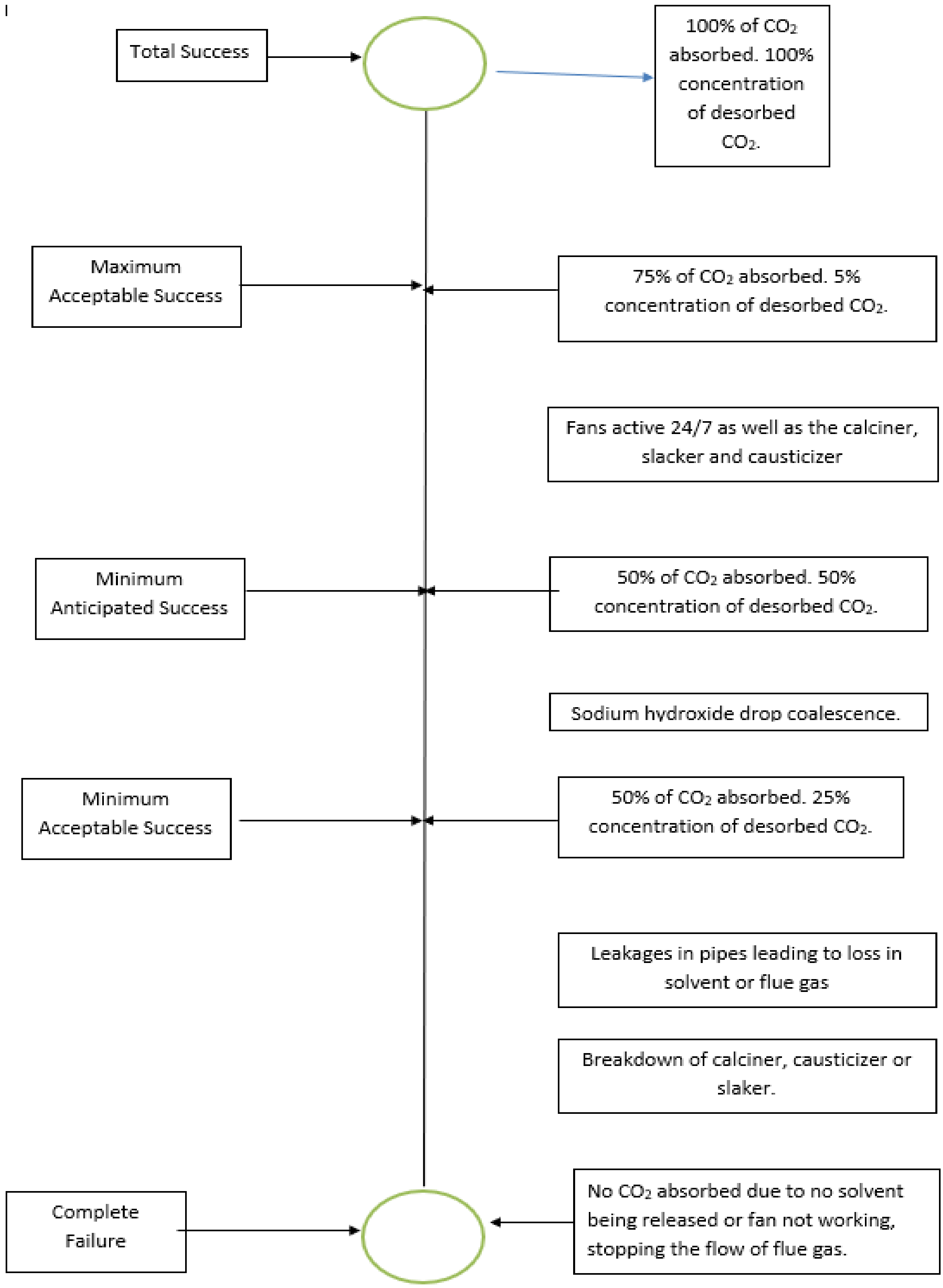
Figure 12: cross section views of carbon processing building

Figure 13: Isometric (left) and side (right) views of the fans used in drawing in the air

In figure 12, the stripped box contains the desorption process, which involves a desorber tank and a condenser, where the CO_2 can then be pumped to either the algae farm or to storage. On the left side, there are the photobioreactors, two algae tanks and a CO_2 pump. One of the algae tanks will be used for culture input to help keep the bioreactors working and the other will be used to collect algae that is ready to be harvested. The CO_2 pump will be used to add CO_2 into the algae photobioreactor so that the algae can absorb it and use it.

RISK MANAGEMENT

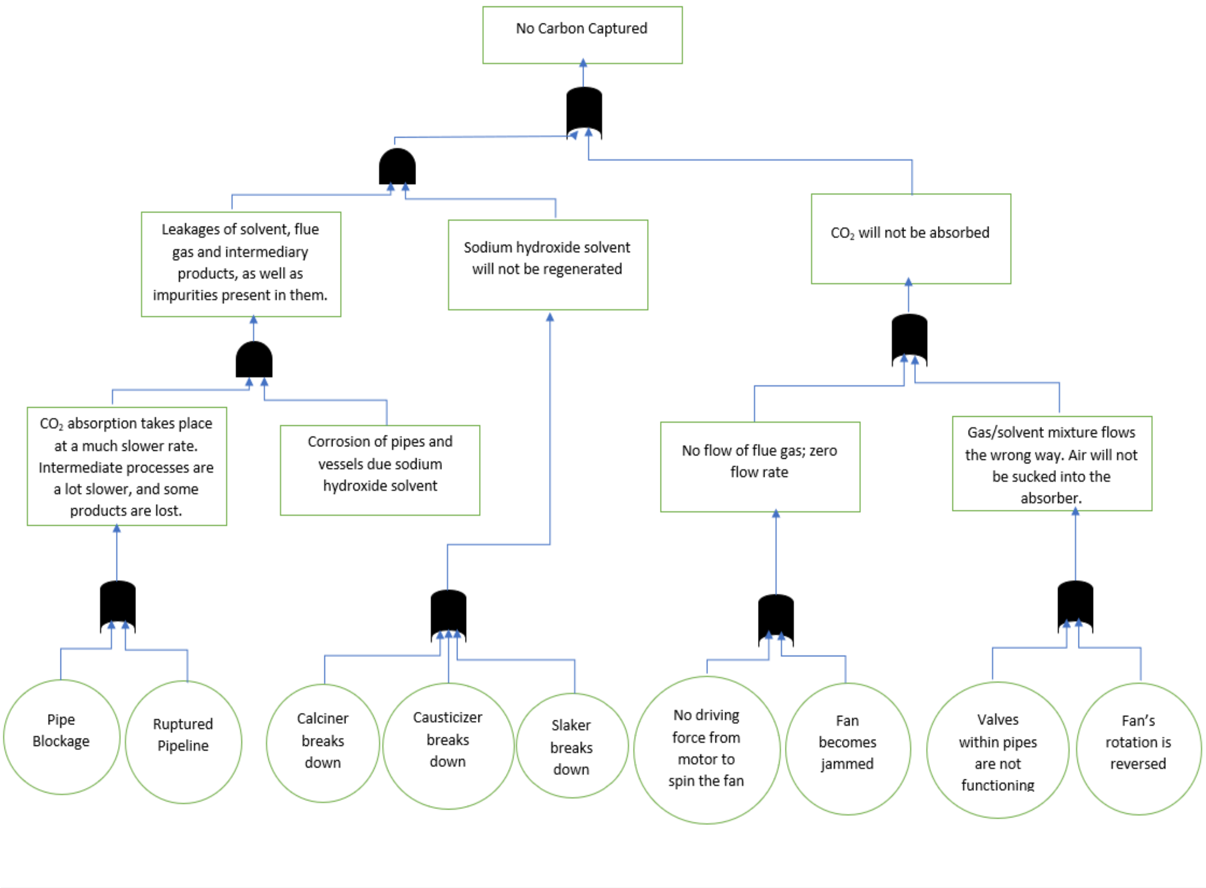
Failure space – Success Space



Hazop

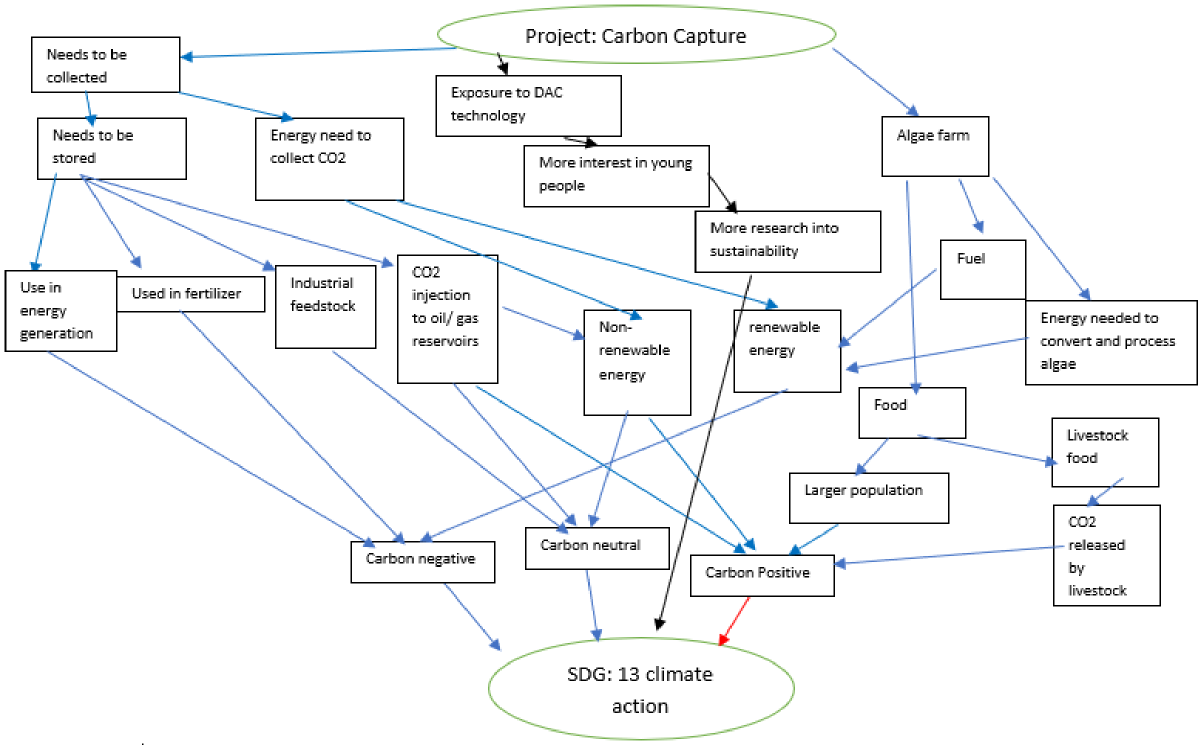
DEVIATION	CAUSE	CONSEQUENCE	ACTIONS & SAFEGUARDS
No fan movement	Loss of power to the motor driving the fan or the fan becoming jammed	Inlet/ flue gas is not cycled into the system so absorption cannot occur	Keep the fan lubricated and have a secondary power source available
Less flow rate of flue gas	Pipeline blockage	Absorption of CO_2 takes place at a much slower rate	The pipelines throughout the system should be checked during downtime or after a every 100 or so cycles.
Reversed flow of flue gas	Human error or equipment failure of valves and pumps. Fans rotating in the opposite direction.	CO_2 absorption will not occur	Maintenance checks should be made on the pumps and valves regularly. Control systems in place to ensure fan rotates in the correct direction and valves operate in the right direction.
Loss of solvent or flue gas	Ruptured pipeline leading to leakage	Decreased rate of absorption if in regards to solvent leakage. Decreased flow rate in regards to flue gas.	Pipe maintenance should be carried out regularly. Pressure gauges should also be installed along the pipes to detect drops in pressure due to leaks.
Increase in pressure due to excessive accumulation of gas	Blockage of gas outlet	Bursting of pipes/containment vessels	Pipe maintenance should be carried out regularly and should be cleaned. Pressure gauges should also be installed along the pipes to detect changes in pressure.
No sodium hydroxide supplied to the absorption column	Could be due a blockage of the solvent inlet or reversed airflow	No CO_2 absorption will occur	Ensure solvent outlet is always kept clear.
No sodium hydroxide regenerated	Breakdown of the calciner, slacker or causticizer	More fresh sodium hydroxide would be required at the initial step of absorption each time, which could lead to a supply problem	Regular maintenance should be carried out on the machines used to regenerate the sodium hydroxide.
Impurities in the flue gas, solvent and intermediate products as well as weakening of the vessel structures	Corrosion of pipes and vessels as sodium hydroxide is very corrosive	Concentration of CO_2 produced would be lower and further waste products maybe produced. These impurities may also interfere with the reactions taking place at each stage.	Using appropriate materials highly resistant to corrosion such as stainless steel as the material/lining for the pipes and absorption tower

FTA


No Carbon Captured
Leakages of solvent, flue gas and intermediary products, as well as impurities present in them.
Sodium hydroxide solvent will not be regenerated
CO_2 will not be absorbed
CO_2 absorption takes place at a much slower rate. Intermediate processes are a lot slower, and some products are lost.
Corrosion of pipes and vessels due sodium hydroxide solvent
No flow of flue gas; zero flow rate
Gas/solvent mixture flows the wrong way. Air will not be sucked into the absorber.
Pipe Blockage
Ruptured Pipeline
Calciner breaks down
Causticizer breaks down
Slaker breaks down
No driving force from motor to spin the fan
Fan becomes jammed
Valves within pipes are not functioning
Fan's rotation is reversed

SUSTAINABILITY

Progression of the United Nations Sustainable Development Goals (SDG)



SDG Goals (including links)	**The SDG target your project could progress (and How)**
GOAL 3: Good Health and Well-being	Less air pollution and cleaner air will result in a longer life expectancy and better overall quality of life.
GOAL 7: Affordable and Clean Energy	Reducing the carbon footprint/emissions produced by the fuels we are using – fossil fuels would not be made carbon neutral although the number of emissions making it to the atmosphere would decrease.
GOAL 9: Industry, Innovation and Infrastructure	Allows for more sustainable industry and infrastructure due to reduced carbon emissions. Moreover, the DAC facility is an example of Negative Emission Technology which means the infrastructure itself shall not be producing any net CO2 emissions.
GOAL 11: Sustainable Cities and Communities	The DAC facility can offset some of the emissions produced in a city allowing for an overall slightly 'healthier' city.
GOAL 12: Responsible Consumption and Production	Taking responsibility for the pollutants we produce by finding ways to capture/store them so that they are not a risk; allows us to be more accountable.

GOAL 13: Climate Action	Will reduce greenhouse gases in the atmosphere thereby reducing CO2 contribution to global warming.
GOAL 17: Partnerships to achieve the Goal	Partner with banks with high ESG for investment into the project.

Life Cycle Analysis

Critical Analysis of Materials - Translation

The direct air capture facility we are designing is required to capture 5000 metric tonnes of carbon dioxide per year. The facility is required to be carbon neutral and sustainable therefore material selection needs to minimise any carbon footprint and environmental impact. The plant life of the facility is 10 years so the materials chosen should have a sustainable end of life in order minimise the carbon impact of the facility through recycling and reuse.

The foundation of the structure is required to support the load from the upper part of the facility, provide overall lateral stability for the structure and provides a level base for the facility to be placed. Desirable material characteristics for the foundation is a high compressive strength and durability to ensure the structure has a reliable and strong foundation.

The roof of the building requires a high corrosion resistance to ensure that the roof lasts for the 10-year plant life without the need for maintenance or replacement. Low thermal conductivity would be a desirable characteristic as the roof would act as an insulator for the facility keeping energy costs low. The roof would also require a high specific strength to get a high strength to weight ratio.

The walls would require high compressive, tensile strength, yield strength and young's modulus; these features are important as the walls are used to support the structure of the building and provide structural integrity to the facility. Low thermal conductivity would be a desirable characteristic as it would insulate the building and reduce the energy costs.

Screening - Foundation

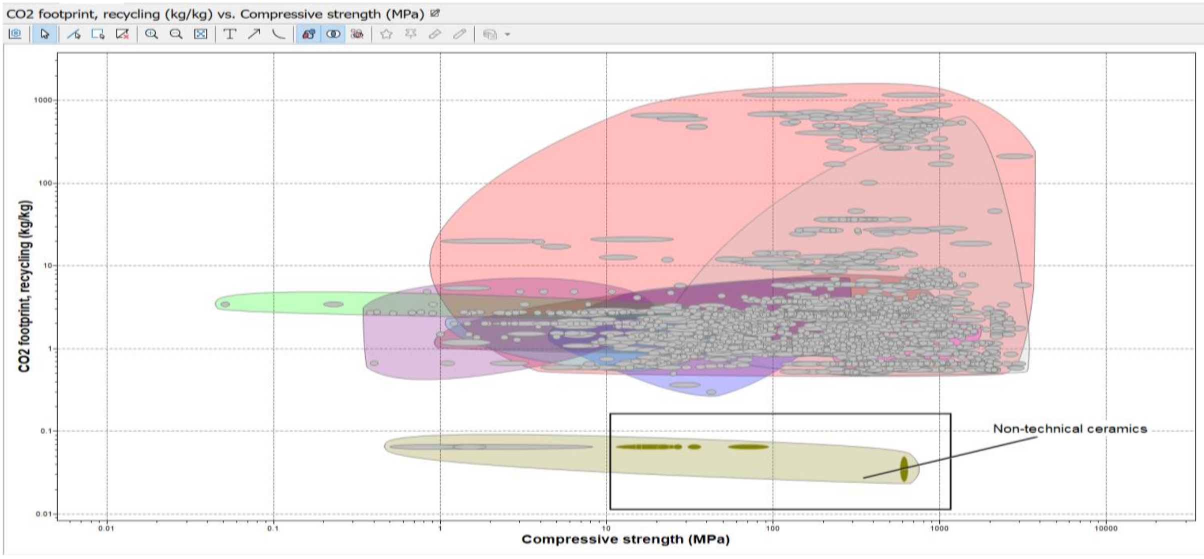


Figure 14. *Bubble chart of CO_2 footprint against compressive strength. The only materials that pass this stage are non-technical ceramics due to their high compressive strength and low carbon footprint.*

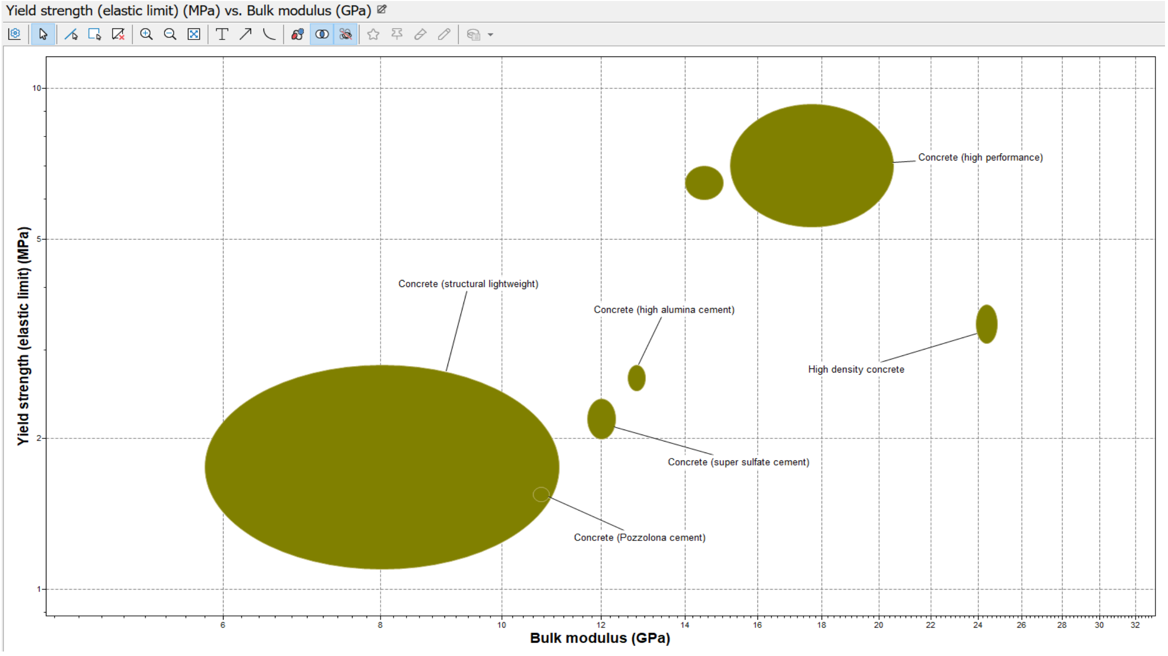


Figure 15. *Bubble chart of yield strength against bulk modulus to rank the appropriate materials chosen.*

The most appropriate materials to use in foundation of the facility are non-technical ceramics as can be seen in figure 14. The materials passed screening due to their desirable characteristics of low CO_2 footprint and high compressive strength. This allows our facility to keep the carbon footprint as low as possible whilst maintaining a high compressive strength to ensure the facility has a strong foundation to withstand natural disasters such as earthquakes, strong winds and floods.

Ranking

The following ranking of materials for the foundation of the facility in order from most appropriate to least:

1. Concrete (high performance)
2. High density concrete
3. Concrete (high alumina cement)
4. Concrete (super sulfate cement)
5. Concrete (Pozzolana cement)
6. Concrete (conducting)
7. Concrete (structural lightweight)

Documentation

Typical foundations are built from masonry [10] such as concrete and brick. These materials are typically chosen as they have a higher compressive strength and higher resistance to corrosion than other options (wood and metals).

Selection

High performance concrete was chosen for its desirable characteristics for the foundation of the facility. It is ideal as it has a high compressive strength, yield strength and bulk modulus compared to the other remaining materials allowing for a stronger foundation.

Roof - Screening

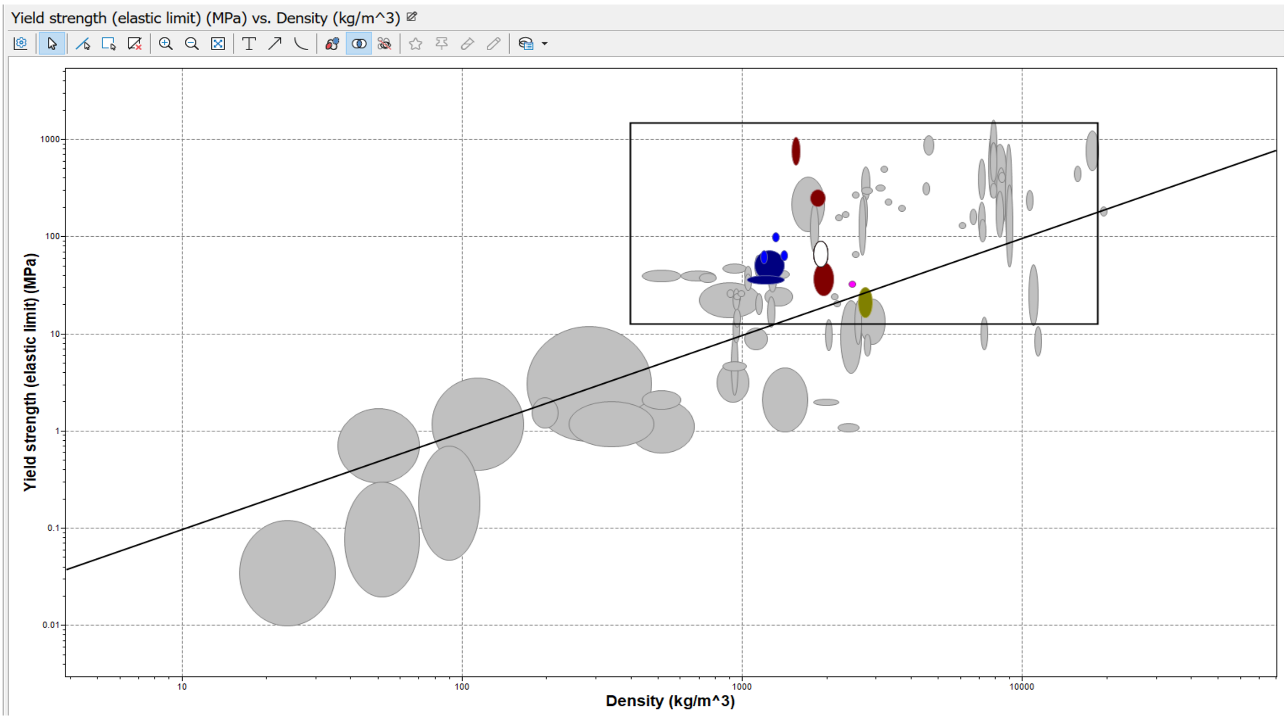


Figure 16. *Bubble chart of yield strength against density and an index line of 1 to eliminate materials which do not have a high specific strength.*

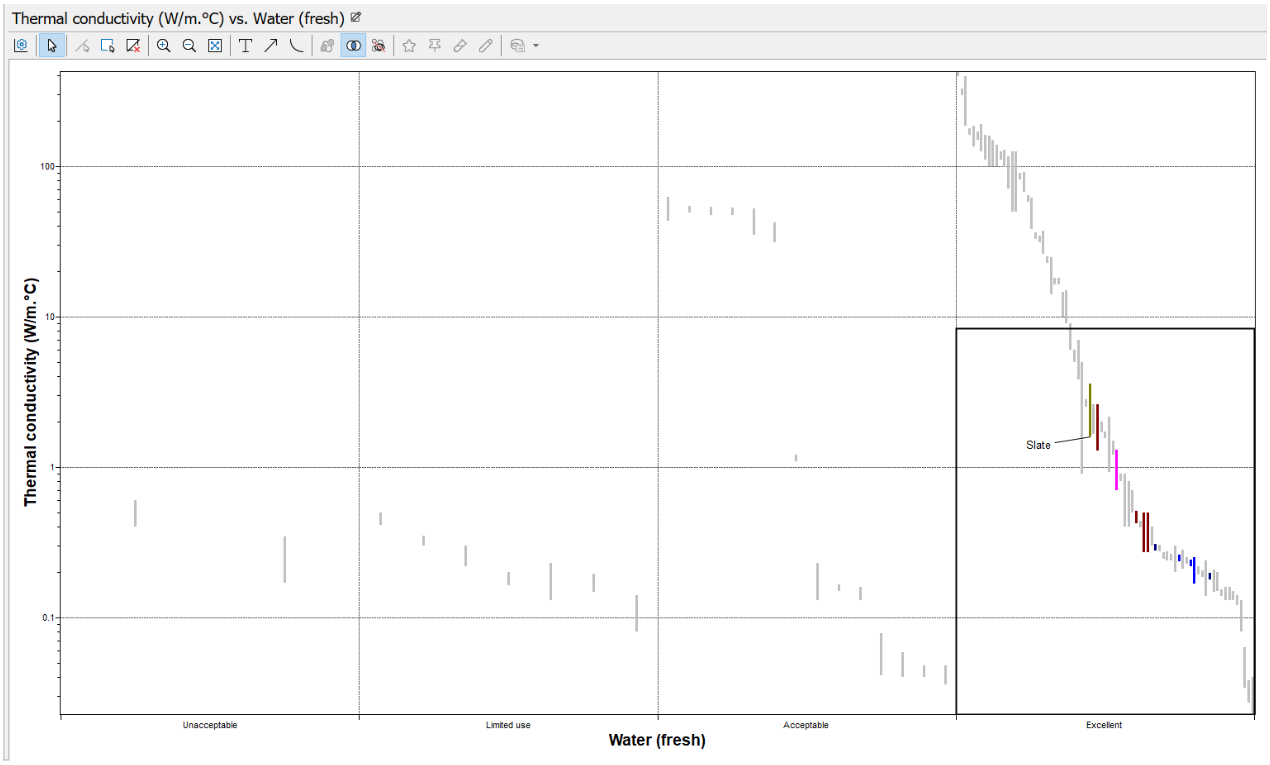


Figure 17. *Bar chart of thermal conductivity against fresh water. Materials with a low thermal conductivity and excellent resistance to fresh water were chosen.*

Figure 18. *Bar chart of compressive strength against critical material risk to further split the remaining materials to get the most appropriate.*

To screen for the most appropriate materials for the roof of the facility a bubble chart was plotted of yield strength against density (figure 17). The use of the index line eliminated materials with a low specific strength. To further analyse the most appropriate materials a bar chart was plotted of thermal conductivity against fresh water to ensure the remaining materials had a high thermal conductivity to insulate the facility and reduce the energy costs. Fresh water was used in this chart as it is important to ensure the remaining materials will not corrode in its presence as Guadalajara is often subject to high amounts of rainfall. The final chart produced was compressive strength against high critical material risk; this was important to conduct so the roof would have structural integrity as well as not requiring any materials which could have possible supply risks as this would increase price of the material and duration in the construction of the facility.

Ranking

1. Slate
2. Sandstone
3. Polyester
4. Sheet moulding compound, SMC, polyester matrix
5. CFRP, epoxy matrix (isotropic)
6. Polyetheretherketone
7. Epoxies

Documentation

Typically, in Mexico, roofs are either poured in place concrete decks or Spanish style tiled roofs [11]. These are aligned and overlapped to carry water away in an effective and efficient manner.

Selection

The material chosen for the roof is sandstone over slate as the roof will be strong enough to hold solar panels as well as provide a long-lasting cover without requiring regular maintenance like slate roofs. However, sandstone tiles have a slightly lower compressive strength than slate tiles but they have a traditional look and will fit into the local environment of Guadalajara.

Wall Structure - Screening

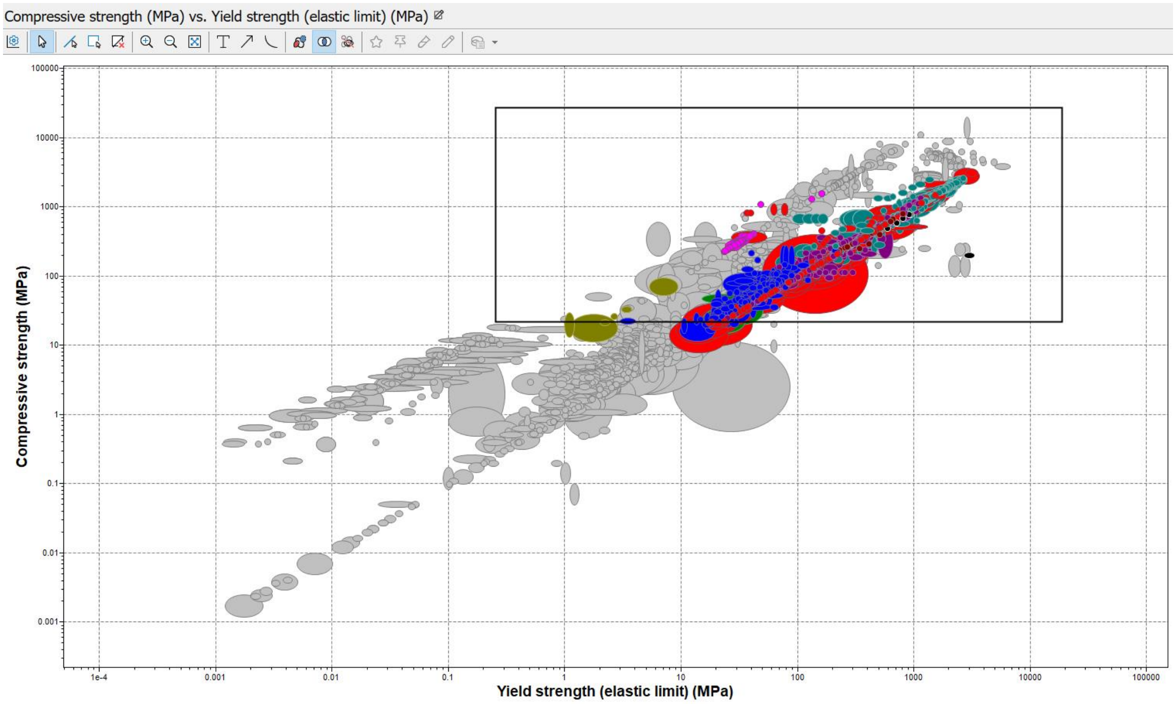


Figure 19. *Bubble chart of compressive strength against yield strength.*

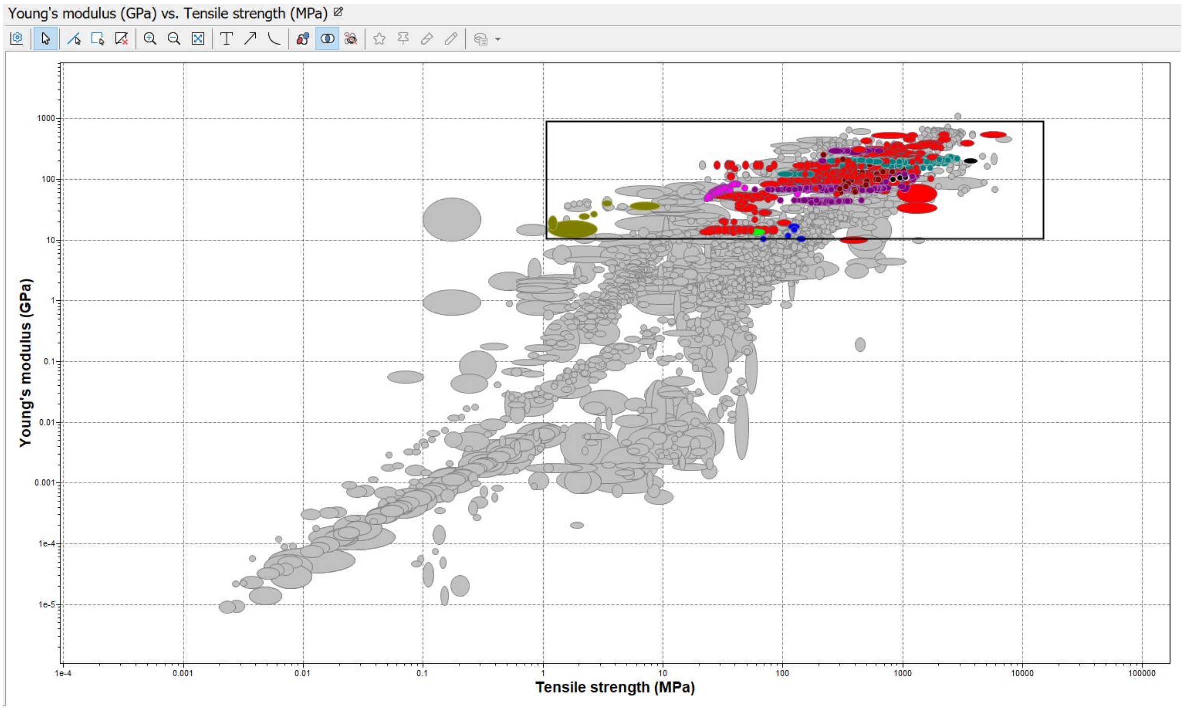


Figure 20. *Bubble chart of young's modulus against tensile strength.*

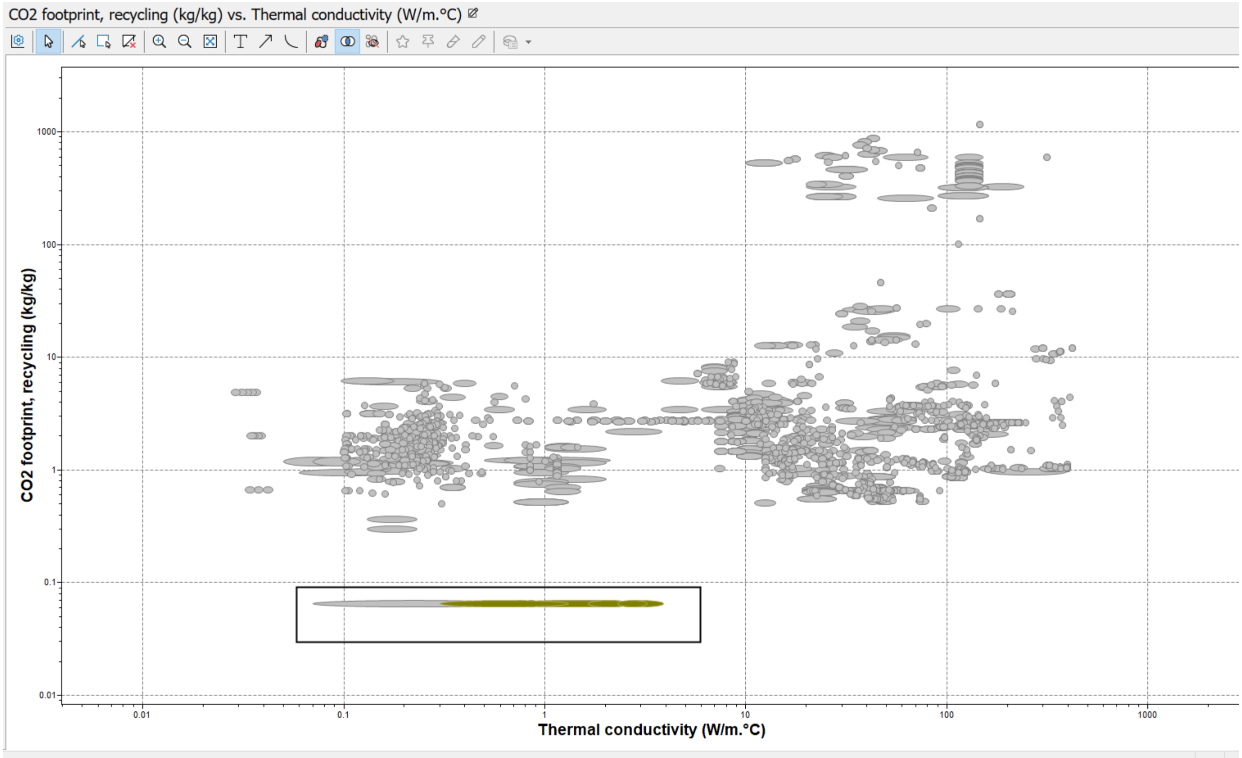


Figure 21. *Bubble chart of carbon dioxide footprint against thermal conductivity.*

To screen for the most appropriate material for wall structure a bubble chart of compressive strength against yield strength (figure 19) was plotted to ensure that only materials with a high yield and compressive strength were chosen. To eliminate the unsuitable materials a bubble chart of young's modulus against tensile strength (figure 20) was plotted to give the materials that had the highest tensile strength and young's modulus. To rank the remaining materials desirable characteristics were compared (figure 21) to give materials with a low thermal conductivity and low carbon footprint.

Ranking

1. Concrete (Structural lightweight)
2. Concrete (super sulfate cement)
3. Concrete (normal, Portland cement)
4. Concrete (high performance)
5. Concrete (high alumina cement)
6. High density concrete

Documentation

Typical Mexico buildings are constructed with brick wall structures with a render applied, often vibrant colour combinations [13].

Selection

Structural lightweight concrete was chosen for the facility as it has a high compressive strength compared to the other remaining materials after screening and a significantly lower thermal conductivity which insulates the building reducing the energy costs.

Comparison Eco Audit

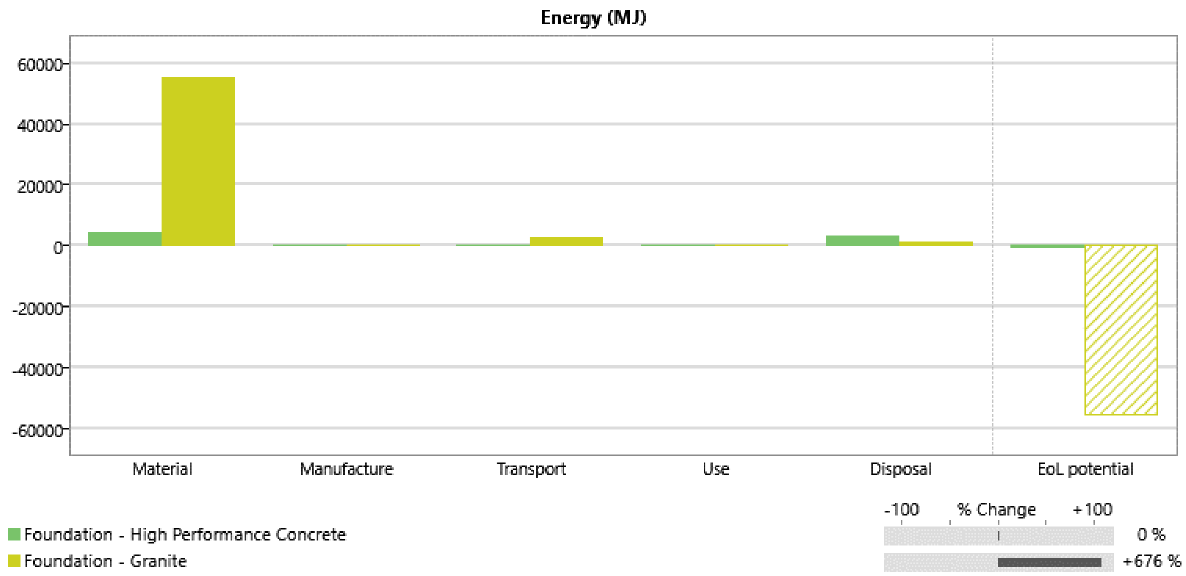


Figure 22. *Energy eco audit comparison between granite and high-performance concrete for the foundation of the DAC facility.*

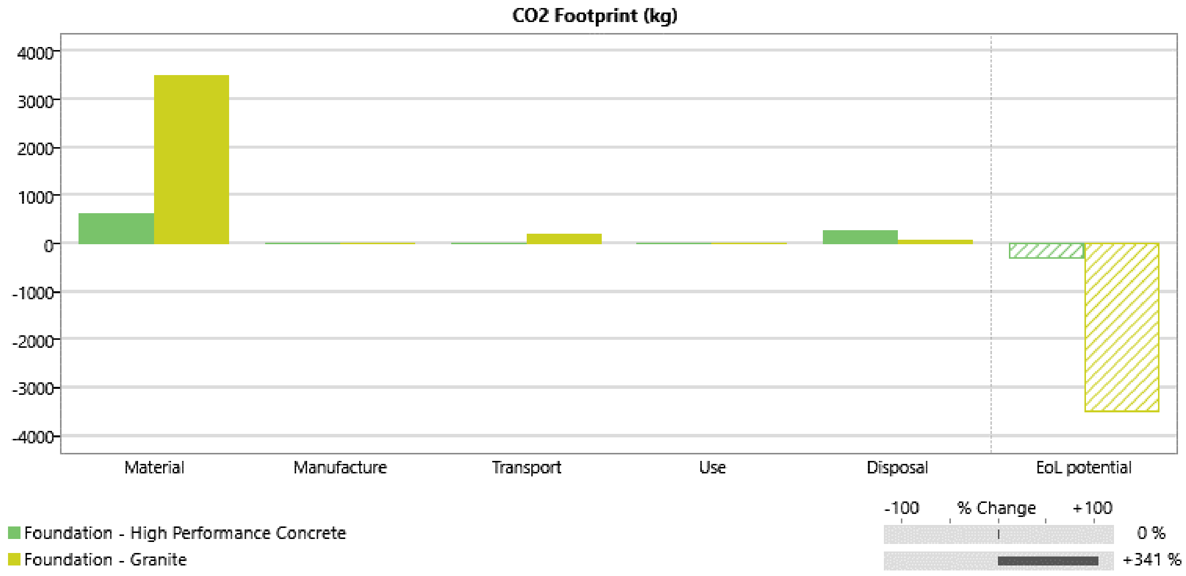


Figure 23. *Carbon footprint eco audit between the high-performance concrete and granite for the foundation of the DAC facility.*

Figures 22 and 23 compare the use of high-performance concrete and granite for the foundation of the facility. High performance concrete was chosen over granite as the energy and carbon dioxide required to obtain the material is significantly higher for granite. The transport of granite requires higher energy and creates a larger carbon dioxide footprint due to the mines in Mexico being located a significant distance from Guadalajara. The disposal of high-performance concrete is slightly more energy intensive than granite however, concrete requires much less energy to obtain than granite.

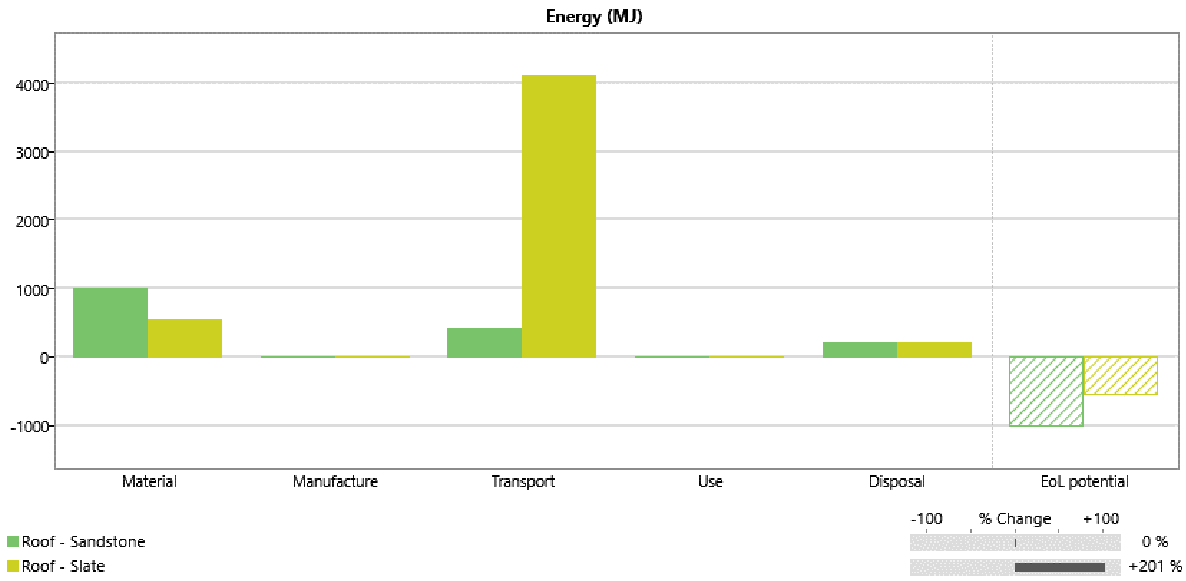


Figure 24. *Energy eco audit comparing the use of sandstone against slate for the roof of the DAC facility.*

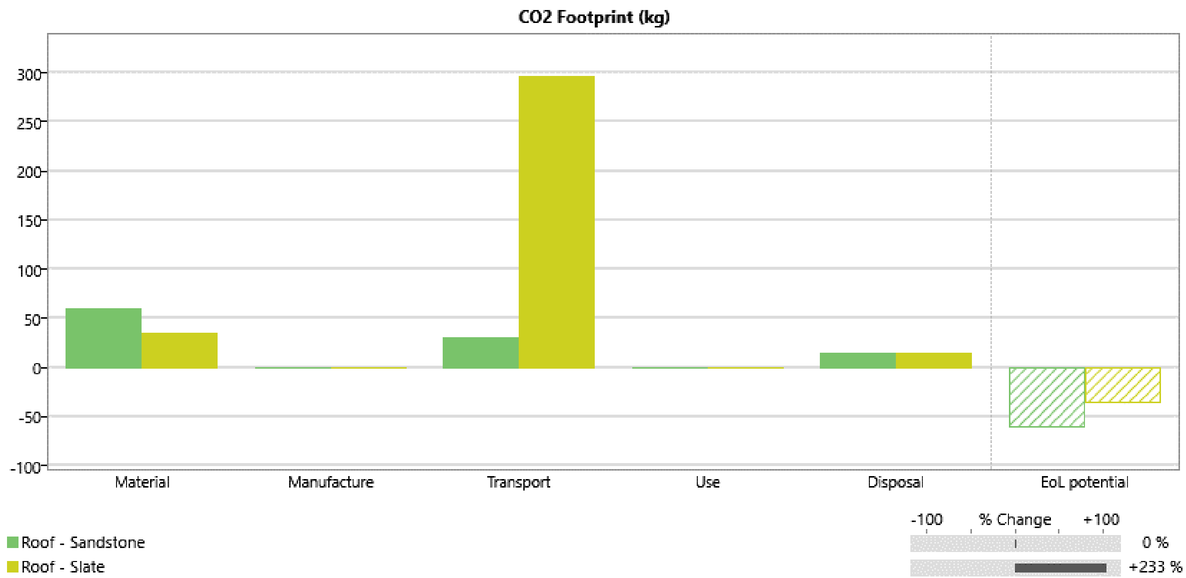


Figure 25. *Carbon eco audit comparing the use of sandstone against slate for the roof of the DAC facility.*

Figures 24 and 25 compare the use of slate and sandstone for the roof of the DAC facility. Both materials require the same amount of energy for disposal however, the end-of-life potential of slate is significantly less than that of sandstone. Energy required in obtaining the material for slate is less than that for sandstone, but the significant difference occurs in the energy and carbon footprint in the transportation stage. As slate is harder to acquire than sandstone in Mexico the carbon dioxide produced, and energy increase is several times larger for slate than sandstone; therefore, the more sustainable option is sandstone.

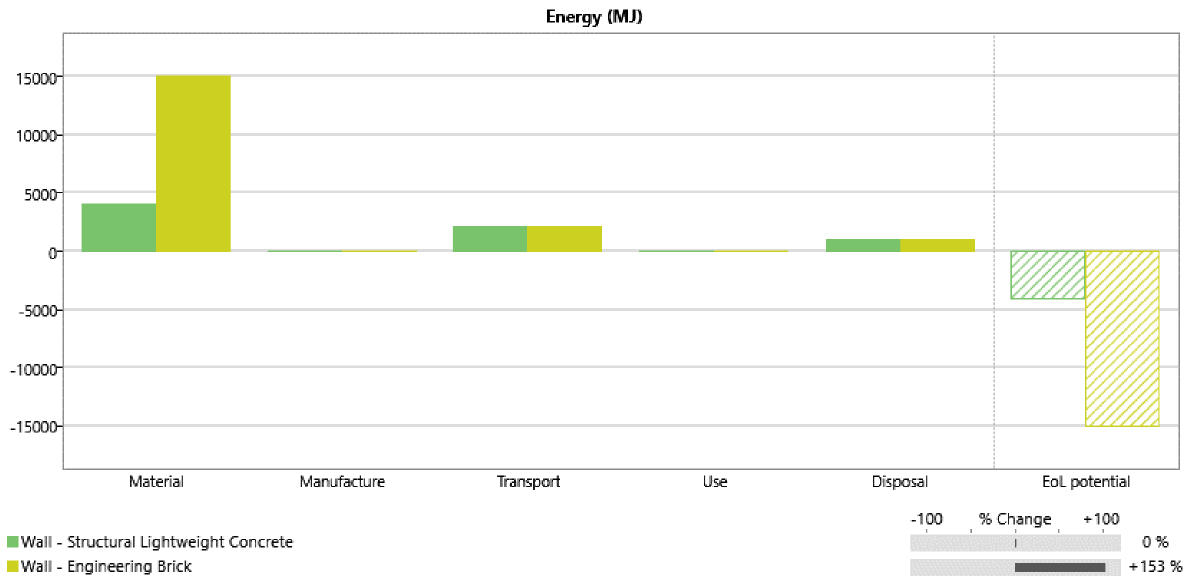


Figure 26. *Energy eco audit comparing wall structures made from engineering brick and structural lightweight concrete.*

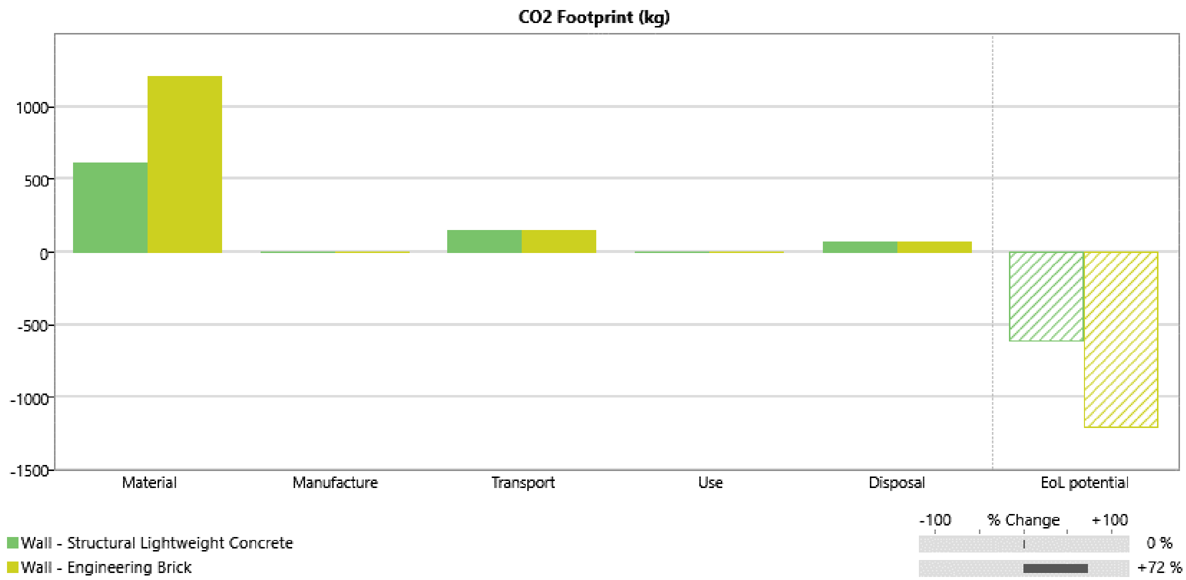


Figure 27. *Carbon eco audit comparing wall structures made from engineering brick and structural lightweight concrete.*

The two best options for the wall structure of the DAC facility are engineering brick and structural lightweight concrete. Both materials require the same amount of energy and cause the same carbon footprint in transport and disposal. The engineering brick requires a more energy intensive process (figure 26) in obtaining the material than lightweight concrete. However, this is matched in the end-of-life phase of engineering brick with a higher recyclability saving more energy than the concrete. The concrete was chosen over engineering brick as the initial carbon footprint (figure 27) and energy requirements are significantly less than those required for engineering brick.

Life Cycle Analysis - Carbon Footprint

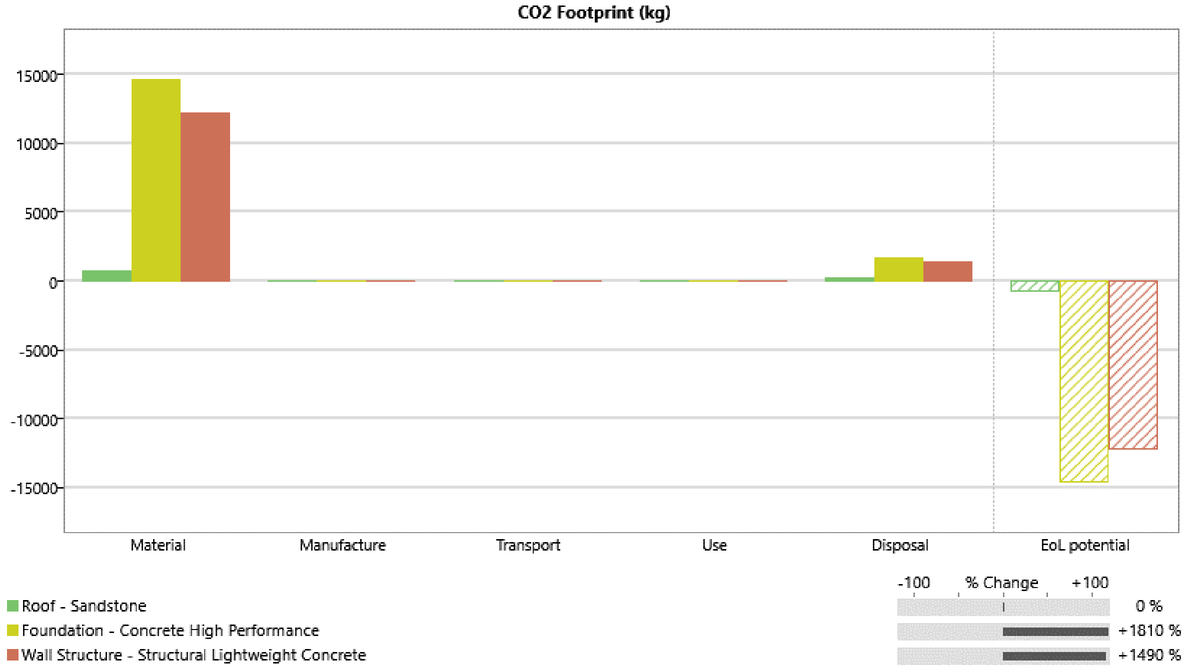


Figure 28. *Carbon footprint of the materials used in the DAC facility.*

The carbon dioxide footprint of the facility can be seen in figure 28 with the main components of the structure being the roof (made from sandstone), the foundation (made from high-performance concrete) and the structural lightweight concrete wall structure. The main carbon footprint is caused by the material and disposal areas of the life cycle. The use and manufacture are extremely low as the materials do not emit large amounts of carbon dioxide from these processes. The material phase has the highest carbon emission due to the processes required in obtaining the raw material. The carbon footprint of the transport stage is also included in the materials section. These materials are sourced locally so transporting them to the location of the facility has a low carbon emission similarly the materials once installed do not use or emit carbon dioxide hence there is no increase in carbon footprint in the usage stage. The disposal of the materials was significantly reduced by maximising the end-of-life potential of the materials through recycling and reuse. The concrete leaves a much higher carbon footprint than the sandstone due to the large amount of concrete required to produce a DAC facility of this size. The facility has a significant carbon footprint however, this was reduced by the large end of life potential of the materials which were chosen for their desirable characteristics and eco-friendly properties from screening which help to reduce the overall impact on the environment through recycling.

Energy Footprint

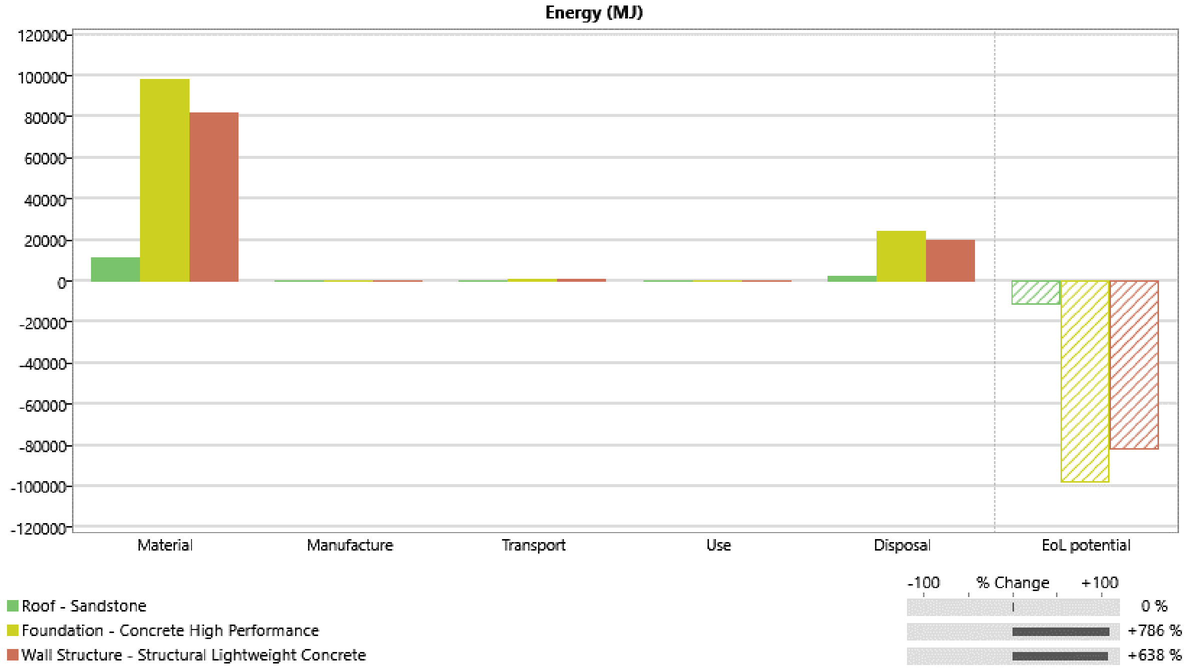


Figure 29. *Bar chart of the total energy required at each stage of the life assessment cycle for the main materials used in the DAC facility.*

The energy requirements to produce the raw material are the most energy intensive in the life cycle analysis. However, this is due to the large amount of material required to build a DAC facility capable of extracting 5000 metric tonnes of carbon dioxide per year. The disposal of the materials is also energy intensive however, this is significantly reduced by the large end of life potential allowing for energy recovery. The high-performance concrete is the most energy intensive of the materials however, this is matched in the high end of life potential to reduce the impact of the material on disposal. The transport of the materials to the site is extremely low due to there being many local sources of these in Guadalajara reducing the energy required in the transport phase. As these materials do not use energy once installed the use phase does not have any energy requirements. Overall, a large amount of energy is required for the materials for the DAC facility but after conducting a life cycle assessment the majority of the energy can be recovered through recycling and reuse of the materials in the end-of-life processes; therefore, minimising the energy impact of the DAC facility.

BUSINESS CASE

Guadalajara is the third largest city in Mexico and is also known as the "Silicon Valley of Mexico". The Guadalajara metropolitan area is one of the prime manufacturing locations in Mexico, contributing 37% to the state of Jalisco's total gross production and 4.42% to the country's economy. Investor friendly policies, strong transportation networks, well established supplier bases and close proximity to Mexican domestic markets are all key drivers for economic activity. By providing a PEST analysis we can establish what factors are essential for the demand and success of our project.

From a political perspective, the government are under pressure to reduce carbon emissions and have targets to reach carbon neutrality to prevent the crisis of global warming. The United Nations created a blueprint to achieve a better and more sustainable future for all. The sustainable development goals were set up in 2015 by the United Nations General Assembly and are intended to be achieved by the year 2030. Goal 7 is of huge significance to our project as it strives to ensure affordable, reliable, sustainable and modern energy access for all. In early 2022, Guadalajara had reached a "Moderate" US Air Quality Index reading of 68 which is an internationally used set of metrics supported by the World Health Organisation to compare air quality in different cities. In Guadalajara specifically, the level of particulate matter 2.5 is over one and a half times the recommended safe level of $10 \mu g/m^3$.

Economically this project may incur great start-up costs however the captured carbon could be sold to businesses/industries that require it and the demand for carbon is expected to increase by 1.7% on a yearly basis. Guadalajara is the third largest city in Mexico and so would always welcome the creation of more jobs. These jobs being: DAC facility workers, algae farm workers and truck drivers. Overall the construction of this DAC facility will not only generate more job opportunities for the local community but it will also increase tax contributions which in turn allows the government a greater budget to reinvest in the city. An increase in money supply from foreign or native investors would promote a positive multiplier effect for the Guadalajara economy.

Technology is continually evolving and it is our responsibility as citizens on Earth to ensure we use our resources to good effect. Although direct air capture facilities and carbon neutrality are fairly modern concepts that we know little of, over the course of this century it's importance will grow exponentially. As a result, the education and maintenance of such facilities will need to be managed. Our facility could be the epicentre of education on carbon capture and energy. It could be used as a teaching facility for the general community or a tourist site. With additional revenue and success with this project the Mexican government could look to invest in more facilities in the future. Over the decades with the education and jobs provided by the facility, generational career progression will begin to occur leading to better income and lifestyles allowing future generations to further improve their lives. This in turn can have a positive change in racial or religious influences as well as social trends.

Finally, there is a lack of effective carbon capture technology in operation and current methods have a very high specific energy requirement. In addition, the sorbents used tend to degrade after multiple cycles which is inefficient and so there are more effective and less energy intensive methods needing to be developed. Currently the captured carbon is being stored underground. A facility like ours would provide the relevant socio-cultural factors and education to provide the foundation for innovative production and storage processes in the future.

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APPENDICES

APPENDIX A: Meeting Log

<summarise all the meetings you had with your group during and the agreed actions>

Week	Agreed Actions	Attendees
1	Completed team roles and researched Guadalajara	YS, HD, HD, EC, AW
2	Delegated roles and research focus	YS, HD, HD, EC, AW, IK
3	Edu pack learning and draft objective trees	HD, HD, EC, AW, IK
4	Complete objective trees and transition to design	YS, HD, HD, EC, AW, IK
5	Divided into report and design teams	YS, HD, HD, EC, AW, IK
6	Finalise report and presentation for submission	YS, HD, HD, EC, AW, IK

APPENDIX B: ACADEMIC MENTOR MEETING FORMS

IDP2 2021/22: Weekly academic mentor meeting record	
Stage-Gate *(you should have a meeting form for each week/stage-gate) Numbers refer to weeks.*	
☒1 INTRO to Plan stage-gate ☐2 PLAN to Research stage-gate ☐3 RESEARCH to Requirements stage-gate ☐4 REQUIREMENTS to Design stage-gate ☐5 DESIGN to Assignment 1 stage-gate	☐7 INTRO to Plan stage-gate ☐8 PLAN to RESEARCH stage-gate ☐9 RESEARCH to Requirements stage-gate ☐10 REQUIREMENTS to Design stage-gate ☐11 DESIGN to Assignment 2 stage-gate

Stage Progress: *(The group should complete this before the meeting). LIST the work you will present to your mentor. Your academic mentor is NOT a subject-matter expert on your challenge. They will discuss and facilitate your group's progress, and provide formative feedback on the work you bring them each week)*

Met group and completed ice breaker activities.

Completed hopes and fears exercise.

Group Structure:

- Air capture and absorption
- CO2 desorption
- CO2 transportation
- CO2 storage

City research – everyone to familiarise with the project. Further roles will be decided on Monday after the lecture.

Yassin – Group Coordinator

Group functioning issues: *(The group should complete this before the meeting) Specific non-technical issues hindering group performance. These may include punctuality, attendance, lack of preparation, disruption, dominant personalities, work quality, and what can be done to improve matters.*

Group functioning well. Every gets along.

What is being done well in this stage and what could be improved *(The academic mentor should complete this). This is your group's formative feedback you should use to improve your work.*

The group has made a good start and seems to be working well together.
There is no issue to resolve.

Initialled Present: HD, YS, EC, HD, AW Absent: None
Group number: 52

Initialled Academic mentor: DTP
Date: 3 February 2022

A copy of this form should be included in the appendices of your report assignments.

IDP2 2021/22: Weekly academic mentor meeting record

Stage-Gate *(you should have a meeting form for each week/stage-gate) Numbers refer to weeks.*

☒1 INTRO to Plan stage-gate	☐7 INTRO to Plan stage-gate
☒2 PLAN to Research stage-gate	☐8 PLAN to RESEARCH stage-gate
☐3 RESEARCH to Requirements stage-gate	☐9 RESEARCH to Requirements stage-gate
☐4 REQUIREMENTS to Design stage-gate	☐10 REQUIREMENTS to Design stage-gate
☐5 DESIGN to Assignment 1 stage-gate	☐11 DESIGN to Assignment 2 stage-gate

Stage Progress: *(The group should complete this before the meeting). LIST the work you will present to your mentor. Your academic mentor is NOT a subject-matter expert on your challenge. They will discuss and facilitate your group's progress, and provide formative feedback on the work you bring them each week)*

On Monday we attended sessions on project management and stage-gate process.

Ibrahim Kabir has joined our group and so there are a total of 6 of us.

We filled out the excel toolset document including the Gantt chart, team working principles, attendance log and the project charter. This has allowed us to set goals and objectives for the upcoming weeks as well as deadlines for these milestones.

Over the weekend we will all do some general research on the specified journals in order to allow each member to familiarise themselves with the overall task so they can select their preferred topic focus.

In the coming week, we will have delegated roles to each team member as well as research focuses.

Group functioning issues: *(The group should complete this before the meeting) Specific non-technical issues hindering group performance. These may include punctuality, attendance, lack of preparation, disruption, dominant personalities, work quality, and what can be done to improve matters.*

None to note so far.

What is being done well in this stage and what could be improved *(The academic mentor should complete this). This is your group's formative feedback you should use to improve your work.*

The group continues working well together. No change is needed.

Initialled Present: YS, HD, IK, EC, AW, HD   Absent:

Group number: 52

Initialled Academic mentor: DP

Date: 10 February 2022

IDP2 2021/22: Weekly academic mentor meeting record	
Stage-Gate *(you should have a meeting form for each week/stage-gate) Numbers refer to weeks.*	
☐1 INTRO to Plan stage-gate ☐2 PLAN to Research stage-gate ☒3 RESEARCH to Requirements stage-gate ☐4 REQUIREMENTS to Design stage-gate ☐5 DESIGN to Assignment 1 stage-gate	☐7 INTRO to Plan stage-gate ☐8 PLAN to RESEARCH stage-gate ☐9 RESEARCH to Requirements stage-gate ☐10 REQUIREMENTS to Design stage-gate ☐11 DESIGN to Assignment 2 stage-gate
Stage Progress: *(The group should complete this before the meeting). LIST the work you will present to your mentor. Your academic mentor is NOT a subject-matter expert on your challenge. They will discuss and facilitate your group's progress, and provide formative feedback on the work you bring them each week)* This week each individual completed research journals on their respective areas. The breakdown structure is as follows: • Reuse - Ethan • Storage - Hilton • Transportation – Harpreet • Absorption and Adsorption – Adam • Desorption – Ibrahim During the lab we completed the sulitest and collated our results into a single document and started a causal diagram for our project. We discussed the research we conducted and the journal papers we summarised. Everyone should learn to use CES Edu pack to conduct material selection and life cycle analysis for the design phase in weeks 4-6. The draft objective tree should be completed in preparation for next week's meeting.	
Group functioning issues: *(The group should complete this before the meeting) Specific non-technical issues hindering group performance. These may include punctuality, attendance, lack of preparation, disruption, dominant personalities, work quality, and what can be done to improve matters.* No issues at the moment.	
What is being done well in this stage and what could be improved *(The academic mentor should complete this). This is your group's formative feedback you should use to improve your work.* The work breakdown structure and the research questions are fine. The group is working effectively. I hope all is well with Yassin and his family.	
Initialled Present: HD, IK, HD, AW, EC Group number: 52	Absent: YS
Initialled Academic mentor: DTP Date: 17-02-2022	

IDP2 2021/22: Weekly academic mentor meeting record	
Stage-Gate *(you should have a meeting form for each week/stage-gate) Numbers refer to weeks.*	
☐1 INTRO to Plan stage-gate ☐2 PLAN to Research stage-gate ☐3 RESEARCH to Requirements stage-gate ☒4 REQUIREMENTS to Design stage-gate ☐5 DESIGN to Assignment 1 stage-gate	☐7 INTRO to Plan stage-gate ☐8 PLAN to RESEARCH stage-gate ☐9 RESEARCH to Requirements stage-gate ☐10 REQUIREMENTS to Design stage-gate ☐11 DESIGN to Assignment 2 stage-gate
Stage Progress: *(The group should complete this before the meeting). LIST the work you will present to your mentor. Your academic mentor is NOT a subject-matter expert on your challenge. They will discuss and facilitate your group's progress, and provide formative feedback on the work you bring them each week)* Filled out risk and reliability worksheet as well as the enterprise worksheet Discussed plan for collating the report. Everyone has their objective tree done or nearly finished. By Monday we will have a completed objective tree to present to you in order to progress onto the design task.	
Group functioning issues: *(The group should complete this before the meeting) Specific non-technical issues hindering group performance. These may include punctuality, attendance, lack of preparation, disruption, dominant personalities, work quality, and what can be done to improve matters.* None	
What is being done well in this stage and what could be improved *(The academic mentor should complete this). This is your group's formative feedback you should use to improve your work.* It seems the group might be slightly behind target. However, team members continue working diligently. I look forward to discussing the objective tree with you next week. Many thanks for accommodating the time change.	
Initialled Present: EC, YS, AW, HD, HD, IK Group number: 52	Absent:
Initialled Academic mentor: DTP Date: 24 February 2022	

IDP2 2021/22: Weekly academic mentor meeting record	
Stage-Gate *(you should have a meeting form for each week/stage-gate) Numbers refer to weeks.*	
☐1 INTRO to Plan stage-gate ☐2 PLAN to Research stage-gate ☐3 RESEARCH to Requirements stage-gate ☒4 REQUIREMENTS to Design stage-gate ☐5 DESIGN to Assignment 1 stage-gate	☐7 INTRO to Plan stage-gate ☐8 PLAN to RESEARCH stage-gate ☐9 RESEARCH to Requirements stage-gate ☐10 REQUIREMENTS to Design stage-gate ☐11 DESIGN to Assignment 2 stage-gate
Stage Progress: *(The group should complete this before the meeting). LIST the work you will present to your mentor. Your academic mentor is NOT a subject-matter expert on your challenge. They will discuss and facilitate your group's progress, and provide formative feedback on the work you bring them each week)* - Assigned final roles for this stage of the project. We split into a design team and a report team. - Hilton, Ethan and Adam will be focusing on the design section and are following the brief we discussed as a team as well as the specification. - Yassin, Harpreet and Ibrahim will be focusing on the report section completing any sections we have yet to finish. - We have discussed our initial designs and are close to settling on a final design to render and draw. - We have attached the completed objective tree for you to look over and offer any feedback. This is a draft and can still be edited if required. - In regards to deadlines we have agreed the final design and the report will be ready for feedback by Monday 7th next week which will give us the final few days to complete the presentation and make any necessary amendments before submission.	
Group functioning issues: *(The group should complete this before the meeting) Specific non-technical issues hindering group performance. These may include punctuality, attendance, lack of preparation, disruption, dominant personalities, work quality, and what can be done to improve matters.* No group issues as usual. Everyone has been delegated roles and tasks to carry out by Monday and everyone was in attendance.	
What is being done well in this stage and what could be improved *(The academic mentor should complete this). This is your group's formative feedback you should use to improve your work.* The functional flow diagram and the CAD work are still to be completed. The group continues to work well.	
Initialled Present: YS, IK, HD, HD, EC, AW Group number: 52	Absent:
Initialled Academic mentor: DP Date: 4 March 2022	

APPENDIX C: RESEARCH JOURNAL CLUB REPORTS

Journal Paper / Book Chapter / Article citation: Direct Air Carbon Capture and Sequestration: How It Works and How It Could Contribute to Climate-Change Mitigation- Ajay Gambhir and Massimo Tavoni

Summary: This article provides an overview of DACs and where the technology is now and how and why it might develop in the future.
Questions (aims): 1. Why are DACs needed? 2. How does a DAC work? 3. What different sorbents can be used? 4. DACs vs CCS 5. Cost of DACs compared to other ways of reducing carbon in the atmosphere 6. What are the ethical issues and ecological impacts of DACs? 7. What are the prospects for using DACs in the future?
Answers (knowledge): 1. DACs are needed to ensure that the world meets the Paris agreement target of keeping the global increase in temperature preferably below 1.5°C. 2. DACs take CO_2 out of ambient air by either absorbing the CO_2, this is when the CO_2 is dissolved in a sorbent material, or the CO_2 is adsorbed, this is when the CO_2 adheres to the surface of the sorbent material. 3. There are several different sorbents that are used currently in DACs to remove CO_2 from the air. Strong liquid bases can be used to absorb the CO_2. Examples of these are potassium hydroxide and sodium hydroxide. These bases dissolve CO_2 forming a carbonate solution which is then reacted with calcium hydroxide to regenerate the base and form calcium carbonate solid which is precipitated out. The solid is then reacted with oxygen at 800°C to form CO_2 and calcium oxide. Calcium oxide is combined with water to form calcium hydroxide which can be reused. The second sorbent used are called amines. This involves a 2 step adsorption process. Step 1 is the adsorption of CO_2 and step 2 involves separating CO_2 at temperatures below 100°C to regenerate the sorbent. Less energy is needed to separate the CO_2 from an amine sorbent as adsorption results in weaker bonds between the CO_2 and sorbent than absorption into a strong base. 4. DAC is more energy and material intensive as CO_2 in ambient air is 100-300 times as diffuse when compared to CO_2 in the chimneys of power stations. This means DAC facilities need much greater surface area of sorbents in contact with ambient air than in contact with flue gases in power station chimneys. Overall current DAC facilities are 3 times as energy intensive per ton of ambient CO_2 removed. 5. Current studies believe that the cost of removing CO_2 from ambient air using DAC is $94-232/t$CO_2$. However, the long term costs are believed to be lower but as the technology isn't yet commercialised it is difficult to know what these costs will be reduced to in the future. A DAC study in Maghreb, North Africa, suggests costs could decrease to $50/t$CO_2$ by 2050 due to the excellent solar potential and the ever reducing costs of solar photovoltaics and batteries. However, these costs are currently higher than other emission reduction strategies such as renewable energy, energy efficiency and fossil fuel CCS. 6. The land use, water removal and ecosystem health impacts are small compared with other technologies that removes CO_2 from the atmosphere. However, water removal during the manufacturing of sorbents may be significant. Also, the chemicals used to

IDP2 Research Journal Club Report

make sorbents and the sorbents themselves need to be disposed of carefully as many of them are highly corrosive or poisonous. The main ethical issue with DAC is that it places a higher burden on future generations to pay for the subsidies used to create DAC facilities and to create the renewable energy sources needed to reduce the CO_2 emissions and therefore the reliance on DAC. 7. DAC facilities will be needed to ensure that the world meets the target of staying below a global temperature increase of 1.5°C as without them that target could be reached within years rather than decades. However, we do not know how easily DAC can be scaled up to meet the necessary demands and without DAC it is estimated that the world would overshoot the 1.5°C target by 0.8°C. To ensure that this won't happen a 20% annual capacity growth will be required for DAC.
Impact: The low concentration of CO_2 in ambient air causes problems for our project and this increases the costs overall for a DAC facility. It shows the importance of powering the facility using clean and cheap renewable energy that is preferably near to the facility. Could the use of new technologies such as batteries and more efficient renewable energy sources decrease the cost of DAC?
Actions: 1. Do further research into reducing the cost of energy sources to reduce the cost of DAC. 2. Do further research into the development of sorbents and the processes to remove CO_2 from ambient air and then store or reuse it.

Journal Paper / Book Chapter / Article citation: Carbon capture and storage: Physical, Chemical, and Biological methods- Surampalli, RY. Chapter 3.2-Separation with Solvents

Summary: Gives an overview of separating CO_2 from flue gases using solvents. Not directly about direct air capture but the technology is still relevant.
Questions (aims): 1. How is CO_2 removed from the air/flue gases? 2. What are the categories of solvents for CO_2 absorption? 3. What are the different options for chemical absorption? 4. What are the options for physical absorption?
Answers (knowledge): 1. Separation involves a 2 step process, absorption and desorption. The optimal temperature for absorption in power stations is 40-60°C and to reach this temperature the flue gases need to be cooled. 2. There are 3 categories of solvents: chemical, physical, and intermediate. 3. Chemical absorption involves CO_2 being absorbed in a liquid solvent by forming chemical bonds between CO_2 and the liquid solvent. The first chemical method is amine absorption. The most mature solution is monoethanolamine (MEA). However, the absorption capacity of MEA solution for CO_2 is very low and requires large volumes to be economical. MEA is also degraded by SOx and NOx. So, amine absorption has developed to diethanolamine (DEA) and methyl diethanolamine (MDEA) to improve this capacity. The second chemical method is aqueous ammonia. This is similar to MEA but has some distinct advantages. SOx and NOx don't degrade ammonia as easily as it does to MEA. It is also believed that there is potential for high CO_2 absorption capacity which, along with the lower amount of degradation, means that aqueous ammonia is more commercially feasible. NH_3 absorbent systems can reach up to 99% CO_2 removal efficiency with a loading capacity of up to 1.2 gCO_2/gNH_3. Whereas MEA absorbent systems can only reach up to 94% CO_2 removal efficiency with a loading capacity of 0.409 gCO_2/gNH_3. Modified Solvay process is the third possible process. This involves reacting sodium chloride with CO_2 in the presence of an ammonia catalyst. The modified version of this process involves changing the ammonia catalyst to MEA or to be even more effective changing it to methylaminoethanol (MAE). The final chemical process involves carbonate-based systems. This process reacts soluble carbonate selectively with CO_2 to form bicarbonate. A university of Texas study shows that this process reduces the energy requirements by 5% and increases the loading capacity by 10% compared to the MEA process. 4. Physical solvents absorb CO_2 without any chemical reactions occurring. To be economically feasible the solvent needs higher CO_2 partial pressures and lower process temperatures. Physical absorption is also weaker than chemical bonding and this makes the absorption-desorption process easier and less energy intensive. Selexol and Rectisol are the most common solvent processes. Dimethyl ether of polyethylene glycol is used as the Selexol solvent. Absorption takes place at a low temperature, 0-5°C. Chilled methanol is used in the Rectisol process. This process normally occurs at -1°C to -38°C. Propylene carbonate is the third process and is more efficient for CO_2 rich streams at high pressure. This makes it less suitable for DAC. Other physical solvents include methanol, N-methyl-2-pyrrolidone, polyethylene glycol dimethylether, propylene carbonate and sulfolane.
Impact: This chapter is about absorption processes for flue gases. Some of these processes wouldn't be feasible for DAC as the concentration of CO_2 in flue gases is considerably higher than in ambient air. This means that many of the processes would have to be modified to be feasible.
Actions: 1. I need to do further research into the feasibility of these absorption processes for DAC facilities. 2. I need to do further research into how these processes have been modified and developed as this paper was published in 2014 and the processes may have been improved in the years since.

Journal Paper / Book Chapter / Article citation: Carbon Capture and Storage: Physical, Chemical, and Biological Methods- Surampalli, RY- Chapter 3.3- Separation with Sorbents

Summary: This chapter provides an overview of the adsorption processes using sorbents that are used to separate CO_2 from flue gases.
Questions (aims): 1. What is physical adsorption? 2. What are the methods of physical adsorption?
Answers (knowledge): 1. Adsorption of CO_2 on physical sorbents is based on intermolecular forces between the molecules of gas and the surface of a solid or a liquid sorbent. The degree of selectivity of CO_2 for adsorption is dependent upon the temperature, partial pressure, surface forces, and pore sizes. However, adsorption is not a preferred method for CO_2 capture in large-scale industrial treatment of flue gases because most of the existing adsorbents have a low capacity and limited selectivity for CO_2 (Meisen and Shuai 1997). 2. The first method of adsorption is using molecular sieves. These molecular sieves can be made from zeolites, e.g., aluminosilicate compositions, or non-zeolites, such as aluminophosphates and silica. This technology is believed to be cost-effective and can be adapted to different carbon sequestration schemes (Yang et al. 2008). The CO_2 adsorption capacity doubled to 1.0 molCO_2/mol surface-bound amine in the presence of water. The second method involves activated carbon. Activated carbon has extremely porous micro- and meso- structure. The CO_2 adsorption capacity is not only dependent on the surface area but on the surface chemistry. In general, the CO_2 capture capacity of activated carbons are lower than zeolites and molecular sieves under low pressure and ambient conditions but higher CO_2 capture capacities at higher pressures, ease of regeneration, potentially as a low-cost alternative, and tolerance to moisture are some of the strengths of activated carbon. This means that activated carbon is unlikely to be used in DAC facilities as this would be a lower pressure and ambient temperature environment and so the CO_2 capture capacity would be low. Naturally occurring and tailor-made zeolites can be used as a method of adsorption. Small pore size zeolites allow smaller gas molecules such as H_2, O_2, and N_2 to pass through, whereas CO_2 is retained. Larger pore size zeolites selectively retain H_2 and other smaller molecules but allow CO_2 to pass through them. The final adsorption method involves Lithium compounds. This method is suitable for high temperature CO_2 adsorption as the reactions are reversible at high temperatures. This method has high capacity, high absorption rate, wide range of temperature and concentrations of CO_2 and stability which makes it a favourable process. However, the global supply of Lithium is low but the future demand for Lithium is high as it is used in electronics and electric vehicle production and so it is unlikely that it would be used for carbon capture technology. Also, as this method is suitable for high temperature environments it wouldn't be suitable for DAC.
Impact: This chapter describes multiple adsorption methods which are used to capture CO_2 from flue gases. However, many of these processes wouldn't be suitable for DAC as they are more suited to high temperature environments rather than ambient conditions.
Actions:

Journal Paper / Book Chapter / Article citation: Carbon capture and storage: Physical, Chemical, and Biological methods- Surampalli, RY- Chapter 3.4- Separation with Membranes

Summary: This chapter gives an overview of how CO_2 can be separated from flue gases using membranes.
Questions (aims): 1. What is membrane separation? 2. How do gas separation membranes work? 3. What are the membrane types?
Answers (knowledge): *1.* CO_2 can be captured using selective membranes which allow the permeation of desired gases through them. The volumetric capacity of the membrane is dependent on the pressure difference across the membrane and therefore high pressure streams are preferred for membrane separation. Membranes can either act like a filter or allow CO_2 to be absorbed into a solvent. *2.* Gas separation membranes consist of solid membrane materials and allow preferential permeation of desired gases. It has several advantages such as high packing density, high flexibility with respect to flow rates and solvent selection and several advantages associated with packed absorption towers. Gas absorption membranes consist of highly dense microporous solid structure in contact with an absorbent solvent. The CO_2 diffuses through the membrane and then this is absorbed by the solvent. Gas absorption favours a higher flux of CO_2 and uses more compact equipment compared to conventional membrane separators. *3.* Polymeric membranes are classified as rubbery or glassy and are based on the glass transition temperature of the polymers used. The rubbery membranes operate just above the glass transition temperature and glassy membranes operate just below the glass transition temperature. Inorganic membranes can be classified into porous and non-porous membranes. Fluxes are higher in the case of porous membranes while higher selectivity can be achieved using non-porous membranes. Inorganic membranes have the ability to operate at high temperatures. Mixed-matrix and hybrid membranes integrated molecular sieves in a polymer membrane. This provides both the permeability of polymers and the selectivity of molecular sieves. Facilitated transport membranes offer higher selectivity and can handle larger throughputs of gas mixture. Higher selectivity is due to the introduction of a carrier agent into the membrane. The CO_2 dissolves and reacts with the carrier agent inside the membrane to form a complex in the membrane. This complex can then be removed.
Impact: This chapter introduces a potential alternative to the traditional adsorption or absorption methods however, many of these methods are more suited to be used to separate CO_2 from flue gases rather than to be used for DAC because this method suits higher pressure and higher concentration air flow which wouldn't be possible for DAC facilities.
Actions: 1. To do further research into more applicable absorption and adsorption methods that can be used in ambient air conditions rather than in power station chimneys.

Journal Paper / Book Chapter / Article citation: Carbon capture and storage, Stephen A. Rackley- Chapter 6- Absorption capture systems

Summary: This part of the chapter provides a detailed description of chemical absorption methods for capturing CO_2.

Questions (aims):

1. What are the fundamentals of absorption?
2. What are the chemical absorption methods?
3. What are the chemical absorption applications and what R&D needs to be done to develop these methods to make them more suitable or economical?

Answers (knowledge):

1. Absorption is distinguished depending on whether the solvent reacts chemically with CO_2 to form chemical compounds or if the solvent is chemically inert and absorbs the CO_2 without a chemical reaction. The first method is chemical absorption, and the second method is physical absorption. To be cost efficient the absorption process needs the following: Fast absorption and desorption rates to minimise equipment size, high loading of CO_2 per unit solvent volume coupled with low solvent cost, low heat of desorption to reduce the energy penalty for solvent regeneration, and solvent tolerance to contaminants to reduce degradation and unwanted by-product formation.

2. Chemical absorption is based on the exothermic reaction of a sorbent with CO_2 in a gas stream, preferably at low temperature. It is particularly suitable for CO_2 capture at low partial pressure, with amine or carbonate solutions being the predominant solvents. Amines are derived from ammonia where one or more of the hydrogen atoms are replaced by organic components or substituents. The most commonly used amine for CO_2 capture is monoethanolamine, MEA, and this acts as a weak base and neutralises the acidic CO_2 molecule.

The maximum loading of MEA is 0.5 molCO_2/mol solvent, but this can be doubled to 1 with bicarbonate forming reactions. This higher value can be reached by using larger amine molecules where the carbamation reaction is hindered. When considering the criteria for effective solvents it is difficult to choose between primary, secondary, or tertiary amines. Generally, the rate of reaction decreases from primary to secondary to tertiary but for regeneration energy and loading capacity the order is reversed. One way to solve this is to create a blend of amine solvents. A faster reaction rate increases the sorption rate, and this allows smaller equipment to be used. SOx and NOx react with amines, and this decreases their absorption capacity. Amines are also corrosive, and this means that corrosion-resistant materials need to be used.

The dissolution of carbonate rocks by carbonic acid removes CO_2 from the atmosphere. This natural process could be sped up and used in power plants where the gas is flowed through a bed of crushed limestone, wetted by water. Regeneration doesn't occur instead the products would be disposed of in the ocean. Regenerable carbonate solutions are available and are used in industrial applications. Potassium carbonate is one of these, but this reaction is slow when the CO_2 pressure is low, but this can be slightly improved by adding amines to the reaction.

Enzyme CA is used as a catalyst to improve both of the methods above.

Ammonia can be used as a solvent, and this has a lower heat of reaction than the equivalent amine-based reaction. This could lead to a significant energy efficiency improvement and cost reduction to an amine system. Ammonia can be used to scrub flue gases by removing NOx and SOx.

Sodium hydroxide can absorb CO_2 through multiple steps. This process uses inexpensive and abundant chemicals but to recover some of the products requires large amounts of energy (15GJ/t-C). A development of this method is to use Sodium trititanate. It is heated to 860°C to start the regeneration process which reduces the energy requirement to 2.9GJ/t-CO_2. Another alternative to this regeneration process is to continuously produce sodium hydroxide by electrolysis of NaCl brine. This has been proposed for a capture system as this would produce solid sodium bicarbonate as a product stream.

Phase-change solvents have been developed to improve the amine solvents. They offer improvements in solvent loading, regeneration energy requirements, stability, and corrosivity compared to amine solvents. 2 types of phase-change have been used: bi-phasic liquid systems and precipitating systems. Bi-phasic solvents form 2 immiscible liquid phases- one phase is CO_2 rich and the other CO_2 lean. The solvents operate as a single homogenous phase at 40°C and separation is induced by CO_2 loading or after heating. After separation only the rich phase needs to be regenerated. This is done at 80-90°C and the CO_2 lean phase is mixed with the regenerated solvent and returned to the absorber. The regeneration energy requirement is significantly reduced due to the lower operating temperature and reduced volume of solvent compared to MEA.

In precipitating systems, high CO_2 loading is achieved without the solvent becoming saturated by removing a precipitated reaction product containing CO_2 and recirculating the lean CO_2 to the absorber. Precipitate is removed as a concentrated slurry from which CO_2 is released by heating and this regenerates the solvent. The main advantages are high solvent loading and high pressure regeneration reducing the energy required for CO_2 compression. The disadvantages are that the precipitates contain SOx and NOx and precipitate build up can damage the equipment.

3. The advantages of amine absorption is that it is a mature technology with low capital costs, range of solvents have been developed and this makes it the benchmark for other solvent systems. The disadvantages are using low amine concentrations to resist corrosion limits the loading capacity, produces hazardous degradation products, low tolerance for SOx, NOx and oxygen in flue gas, high energy requirement for sorbent regeneration, and solvent loss due to mist formation.

   The areas for research are evaluation of new amine solvents, catalysed absorption and regeneration/desorption, additives to improve system performance, process improvements to improve heat integration, increase solvent capacity and reduce solvent loss, quantum-chemical modelling to predict solvent properties, and performance of precipitating amine and amino acid solvents.

   The advantages of bi-phasic liquid solvents are higher solvent loading capacity, regeneration at higher pressure and lower temperature to reduce energy requirements, and lower corrosivity than standard amine solvents.

   The disadvantage is that it has a higher loaded solvent viscosity than amines, including higher process pressure drops.

   The areas for research are regulation of solvent phase-change, alternative desorption techniques, identification of degradation products, and the development and validation of liquid: liquid phase-change thermodynamic models.

   The advantages of Potassium carbonate systems are the higher solvent loading capacity, lower regeneration energy requirement, lower corrosivity, and low solvent cost.

The disadvantages are the slow reaction rate without promoters such as piperazine, high cost of additives such as piperazine, and system fouling due to reaction product precipitation. The areas for research are the energy saving through improved tower packing and multistage stripping, alternative additives to improve CO_2 absorption rate and reduce stripping heat requirement, and precipitating systems to reduce regeneration energy. The advantages of using aqueous ammonia are the low regeneration energy requirement, lack of solvent degradation during the absorption and regeneration cycle, low solvent cost, high pressure regeneration, tolerant to oxygen and other contaminants, and the ammonium sulphate and ammonium nitrate formed as by-products can be sold as fertiliser. The disadvantages are the high solvent volatility requiring reduced operating temperatures and the high solvent loss during regeneration at high temperature. The areas for research are increasing solvent loading and reaction rate through process optimisation, reducing solvent losses, and integration with industrial production of ammonium bicarbonate fertiliser. The advantages of sodium hydroxide are the low-cost and abundance of chemicals, and all process steps are currently proven technologies applied in other industries. The disadvantages of sodium hydroxide are the high energy requirement in calcining intermediate regeneration product (Calcium carbonate), and high water and solvent loss in spray tower contactor. The areas for research are alternative methods of solvent recovery, laboratory-scale spray tower optimisation and commercial-scale concept development, and process simulation and optimisation. Amine absorption deployed in the Petra Nova project absorbs 4800 t-CO_2/day. This is a process to absorb CO_2 from flue gases. The reboiler energy requirement for a 30 wt% MEA solvent is 3.7 GJ/t-CO_2 and this value is considered as a benchmark for other processes. All chemical absorption processes have a similar setup with an absorber tower which separates the CO_2 and then this CO_2 is then sent to another tower where the gases can be stripped, or the solvent can be regenerated depending on the process.
4. **Impact:** This chapter gives a very detailed look into current chemical absorption technologies especially for their use to capture CO_2 from flue gases. It also highlights areas where research and development need to be done to improve the process. However, most of the research in this chapter is about current technologies and their use in power stations to remove CO_2 from flue gases. This isn't necessarily suitable for our project as many of these processes wouldn't work for DAC.
Actions: 1. To do further research into how any of these processes could be used in DAC facilities. 2. To do research into what technologies are currently used in DAC facilities.

Journal Paper / Book Chapter / Article citation: Carbon capture and storage, Stephen A. Rackley- Chapter 6- Absorption capture systems

Summary: This part of the chapter gives a detailed look into physical absorption processes for carbon captures process mainly for flue gases.

Questions (aims):

1. What are the physical absorption methods?
2. What are the applications for physical absorption methods and is there any suggested research that should be done to improve these processes?

Answers (knowledge):

1. Physical absorption processes use organic or inorganic physical solvents to absorb CO_2 rather than reacting with them chemically. The amount of gas dissolved in unit volume of a solvent is proportional to the partial pressure of the gas in equilibrium with the solvent. The advantage over chemical absorption is that the heat required for desorption is significantly lower. This also necessitates low operating temperatures at the absorption stage to achieve high solvent loading. Methanol is used as a physical solvent in the Rectisol process, and this means that the most effective temperature for CO_2 separation is in the range -60°C to -70°C.

2. The advantages of the Flour process (propylene carbonate) are that it is a well proven technology, highly selective for CO_2 relative to methane, and a non-corrosive solvent. The disadvantages are low H_2S tolerance in gas stream, feed gas must be dehydrated due to high water solubility, and that the irreversible reaction with CO_2 and water at 90°C precludes temperature swing regeneration.

The advantages of the Rectisol process (chilled methanol) are that it is highly selective for CO_2, able to remove many contaminants in a single process, low solvent cost, and long-proven application in gasification projects.

The disadvantages are the high refrigeration energy cost, solvent volatility and emissions concerns, higher selectivity for H_2S over CO_2, and the feed gas must be dehydrated due to high water solubility.

The advantages of the Selexol process (DMEPG) are that it is a well proven technology, a chemically inert solvent that isn't subject to degradation with very low vapour pressure, non-aqueous solvent that allows low-cost carbon steel plant construction, and it is a dual stage process that can capture CO_2 and H_2S.

The disadvantages are the high partial pressure of CO_2 that is required, the high solvent viscosity, and high solvent costs.

The areas for research to improve the Selexol process are additives to reduce solvent costs, and process optimisation to reduce energy requirements and operating costs.

As physical absorption is favoured at high pressure it is more suited to applications such as CO_2 recovery from a produced natural gas stream. Whereas chemical absorption is preferred for low pressure applications such as CO_2 capture from flue gases.

All physical absorption processes require the gas to be passed through an absorber tower. Sometimes before this the gas has to be passed through a heat exchanger to ensure that the gas is at the right temperature to be put into the absorber tower.

Impact: This part of the chapter gives a good description of some of the current physical absorption processes and the advantages and negatives of them. Most of these processes however wouldn't be suitable for DAC facilities as they are mainly suited to high pressure conditions which doesn't match with the ambient conditions for our DAC facility.

Journal Paper / Book Chapter / Article citation: Carbon capture and storage, Stephen A. Rackley- Chapter 6- Absorption capture systems

Summary: This part of the chapter gives a detailed description of the research and development that is being done or needs to be done to improve the current processes.
Questions (aims): 1. What R&D is currently being done to develop absorption technology? 2. What current DAC technology is being developed?
Answers (knowledge): *1.* The fundamental challenge that is trying to be solved by doing R&D is to reduce the overall process energy requirement, particularly the energy required for solvent regeneration. Early amine systems required 3.7 GJ/t-CO2 captured for solvent regeneration, but the current achievable level for amine systems is 2.6 GJ/t-CO2. Research on new mixed solvents, such as bi-phasic amine solvents, has reduced this to 2.0 GJ/t-CO2, and results on catalytic regeneration promises further reduction to 1.1 GJ/t-CO2, however both of these lower values are lab-measured values. Since the theoretical minimum work of separation of CO2 from flue gas is 0.2 GJ/t-CO2, the potential for improvement remains. Catalysed aqueous carbonate solvent is being developed to improve its commercial performance in coal and natural gas flue gases. Initial commercial deployments aim to capture 30 t-CO_2/day from a pulp mill and to capture 300 t-CO_2/day from enhanced oil recovery. These projects use two 6m^3 rotating packed beds (RPB) rather than a 370m^3 absorber tower which reduces the capital costs. A potassium carbonate precipitating system is being trialled in an industrial pilot capturing 1 t-CO_2/day where the regeneration energy is low, low overall costs and good environmental performance. Many of the limitations of the current solvent systems such as corrosivity, solvent loss, susceptibility to degradation, and absorption efficiency loss which arise due to the direct contact between the solvent and the flue gas. A way to mitigate these problems is to isolate the solvent by encapsulating it within a permeable shell. One way to do this is to mix the solvent with silica nanoparticles and these particles act like a dry powder. This method showed improved absorption capacity, but the solvent had to be heated using microwave absorption to make the solvent regeneration step efficient. The second method is micro-encapsulated carbon sorbents (MECS) use a solid rather than a powder shell. Compared to a standard packed tower absorber, the fabricated microcapsules exhibited a 10-100 fold increase in surface area per unit solvent volume and the absorption rate could be increased by adding Zn-cyclen. More R&D needs to be done to test the sustainability of microencapsulation, but the early signs are promising for use in carbon capture in flue gases. 2. Sodium hydroxide is starting to be used for DAC. For the capture of CO_2 from flue gases the partial pressure of CO_2 varies from 15kPa to >10MPa however, for CO_2 capture from ambient air the partial pressure of CO_2 is around 40Pa. The theoretical minimum energy required to capture CO_2 from ambient air is around 1 GJ/t-CO_2 (4 GJ/t-C). This includes the energy required to compress the captured CO_2 to 10MPa needed for geological storage (at 50% efficiency). For a DAC facility using NaOH the air is drawn through a contactor where the CO_2 is captured by the solvent. The contactor could be a packed tower configuration, where the

solvent drips down through packing material designed to maximise contact area, or it could be an empty tower similar to the evaporative cooling tower of a power plant, where a solvent spray dropping in a downward air flow. 50% efficiency is estimated to be achievable with a 1.5m high packed bed or a 100m high spray tower. The Sodium carbonate formed is then sent through a causticizer where it reacts with calcium hydroxide to form calcium carbonate which is then sent to a calciner where it is separated into calcium oxide, which can be used to regenerate the sodium hydroxide, and CO_2. A 6 m high packed tower under development at the Energy and Environmental Systems Group at the University of Calgary. The tower achieves a CO_2 reduction of 200 ppm with a solvent flow rate of 5 L/s and an air flow speed of 1.25 m/s, at an energy cost of 290 MJ/t-CO2 and has a capture capacity of 15 t-CO2/year per m^2 of absorption cross section. An interesting result achieved in these experiments is that the capture performance of the tower falls off only gradually if the solvent supply is interrupted. Intermittent supply of solvent to the tower saves on energy required to pump the solvent, and 85% of the capture performance can be achieved with a 5% solvent pump duty cycle. Evaporative water loss is a potentially significant issue for this type of contactor; a water loss of 20 mol-H_2O/mol-CO_2 (6.4 t-H_2O/t-CO_2) was determined for a previous version of a contacting tower (open spray tower rather than packed tower). One way to improve the efficiency of this process is to integrate heat recovery processes for the steam produced in the calciner and the low-level heat from the exothermic slaking reaction. This process has a high energy cost due to the calcining and a high capital cost for the contacting system compared to the capture process for flue gases. To avoid using a calciner an alternative process can be used. This process uses the titanate cycle to regenerate the caustic solvent. Further research on this processes is trying to improve the kinetics of the absorption and regeneration steps to optimise the efficiency and trying to design a 1 Mt-CO_2/year air capture unit. A contacting system of this capacity could take the form of a segmented vertical slab. Prevailing winds, assisted by a fan wall, would sustain a horizontal air flow of 2-5 m/s while the solvent falls though a packed wall with vertically oriented packing plates, optimized to maximize liquid hold-up under intermittent flow conditions. Solvent supply would be switched sequentially between slab sections, allowing intermittent wetting of individual sections with continuous pump operation. A 1 Mt-CO_2/year air capture unit with a capture capacity of 20 t-CO_2/ m^2 year would require a 10m high contactor slab of 5km length. The cost per tonne of CO_2 captured for this system has been estimated to exceed \$300/t-CO_2, which is significantly more than capture of CO_2 from flue gases.
Impact: This part of the chapter gives an overview of how these absorption technologies could have been developed since it was written in 2017 or how the technologies could be developed in the future. This chapter also gives an early look at what absorption processes some of the early DAC facilities and systems use and the positives and negatives of these.
Actions: How are you going to follow-up to progress your project work? 1. Research how applicable the technologies used in early DAC facilities are for our DAC project. 2. To do further research into how these technologies have developed and if any other technologies are used in newer DAC facilities. 3. To do research into what sort of packing tower is the best for our facility.

Journal Paper / Book Chapter / Article citation: Direct Air Capture- IEA Tracking Report November 2021- Sara Budinis

Summary: This article gives an overview of the 19 DAC facilities currently in operation.
Questions (aims): 1. What sort of solvents are used and why? 2. What is the future for DAC plants?
Answers (knowledge): *1.* The current facilities either use liquid or solid solvents. Liquid systems use a chemical solution, often a hydroxide solution, which captures the CO_2 and then this solvent is regenerated by applying high temperatures to the air. Solid solvents chemically bind with CO_2 to capture it. These solvents are heated and placed under a vacuum to release the CO_2 so it can be stored or reused. The location of the facility is often decided due to needing to be located near to an energy source. To get the most negative emission system the facility needs to be powered by renewable energy sources or maybe even low-grade waste heat. To store liquid captured CO_2 requires total energy of 6.57 GJ/tCO_2 but to reuse it only requires 6.09 GJ/tCO_2 due to saving electricity used. This is lower than the energy required using solid solvents which would require 10.02 GJ/tCO_2 to store the CO_2 and would require 9.54 GJ/tCO_2 to reuse the CO_2. A study released by Carbon Engineering suggested that the costs of capture could be feasibly reduced to \$94-\$232/tCO_2 depending on energy costs and plant configuration. 2. There are 19 facilities that capture more than 0.01 MtCO_2/year in the world but a new facility which will be operational in 2024 plans to be able to capture 1 MtCO_2/year using Potassium hydroxide liquid solvent. Companies are investing in DAC facilities to help offset their greenhouse gas emissions. Some companies invest in facilities, but others pay for subscriptions which range from \$600-\$1000/tCO_2 to remove CO_2 from the atmosphere. The 1 MtCO_2/year will be the first large-scale DAC facility and will show how well the technology scales up and this will be important because if the world wants to meet the net zero emissions by 2050 scenario, capture needs to be scaled up to 85 MtCO_2/year by 2030 and to 980 MtCO_2/year by 2050 and both of these are significantly larger than the current capacity.
Impact: This article gives an overview of what technology is currently used and how this technology could feasibly improve in the near future and so this will help to design our DAC facility which could take advantage of some of these developments.
Actions: 1. To research the liquid solvent process to work out the potential hourly capture rate. 2. To research the packing needed to optimise this process.

Journal Paper / Book Chapter / Article citation: https://www.machengineering.com/random-packing-vs-structured-packing/

Summary: Gives an overview of random packing vs structured packing for absorbing CO_2 from ambient air.
Questions (aims): 1. What is random packing? 2. What types of random packing are available? 3. What are the benefits of random packing? 4. What is structured packing? 5. What types of structured packing are available? 6. What are the benefits of structured packing?
Answers (knowledge): 1. Random packing uses small pieces of packing designed to form a large surface area where reactants interact while minimising complexity within the column. Random packing is designed to maximise surface-to-volume ratio and minimise the pressure drop. Large random packing pieces have a high capacity but low efficiency whereas small random packing pieces have a lower capacity but a high efficiency. A desired characteristic for random packing is a low pressure drop because a high pressure drop decreases both the performance and efficiency. 2. Raschig rings are small pieces of tube where the length equals the width. The surface is smooth and has no holes. This means that they have a low capacity and low efficiency as well as a relatively high cost. However, Raschig rings are highly corrosion-resistant. Pall rings are more sophisticated Raschig rings. They have added internal support structures and external surfacing textures. These features mean that Pall rings have a significantly higher capacity and efficiency. These characteristics make Pall rings good for distillation and absorption. Saddle rings come in two sorts: Berl saddles and Intalox saddles. These pieces are shaped like tiny saddles where the length exceeds the diameter. The pieces have small holes and grooves on the exterior surface to increase the surface area and increase the contact opportunity. This makes saddle rings ideal for chemical distillation, stripping and absorption. Lessing rings are ceramic and have internal partitions to increase surface area and enhance efficiency. As they are made of ceramic these rings are highly resistant to heat and corrosion. So, they are ideal for regenerative oxide systems. Tri-packs have a spherical shape so are not prone to nesting or settling. Interior ribs maximise surface area and wetting qualities. This helps this form of packing to achieve low pressure drop and high mass transfer rates. They are made from a range of plastics providing corrosion and temperature resistance. 3. Most applications use random packing as it is much less expensive compared to structured packing. Random packing also has improved contact area, mass transfer and efficiency compared to older packing technology such as tray technology. 4. Structured packing is organised packing aimed to channel liquid material into a specific shape. The discs are made from metal, plastic or porcelain which contain internal structures arranged into different honeycomb shapes. These provide a large surface area for the liquid to contact without causing resistance that impedes the liquid's flow.

The packing forces the liquid into specific, preordained arrangements within the column. The large pieces of material contain holes, grooves, and corrugation amongst other texture elements with the aim to increase surface area and contact ability.
Common applications for structured packing are to store liquid in processing plants and to counterbalance the effects of the constant motion of offshore drilling plants by preventing the liquid from spreading.

5. There are 3 main types of structured packing. The first is knitted wire structured packing. This is made up of a multitude of small wires of knitted packing which aims to offer a large surface area and efficient mass transfer.
The second type is gauze. This is used for applications that require the lowest possible pressure drop. Examples of these applications are processing pharmaceuticals and other chemicals that require this process to be done in a specific temperature range.
The third type of structured packing is corrugated structured packing. Common uses for this include vacuum distillation and high-pressure absorption. This form of packing is stronger and more durable than knitted packing and gauze. It can also process much higher volumes of liquid and vapour. An advantage of corrugated grid sheet metal is that due to its smooth and open surface it has some resistance to chemical fouling. This makes it ideal for applications in environments such as wastewater and other fouling-prone environments.
6. A benefit of structured packing is that it spreads liquid into a thin film, to create contact opportunities and therefore enhance performance. Liquid spreading is important in low-pressure applications where internal pressure alone cannot be relied upon to spread the liquid.
Structed packing also has the advantages of having a smaller pressure drop than random packing and can handle larger flow volumes. This allows for higher volatility, which increases energy efficiency and reduces foaming.
Structured packing has a tightly organised infrastructure, which increases efficiency and allows it to pack a larger volume. This higher capacity can lead to increased operating rates.
The disadvantage of structured packing is that it is more expensive than random packing. Random packing can vary in cost from \$6-100 ft^3 whereas structured packing can vary in cost from \$45-400 ft^3.

Impact: This article gives an overview of all the different types of packing that could be used in the absorber tower and suggests that structured packing is good for low pressure environments which would make it suitable for DAC applications. Structured packing also performances better than random packing and so as long as the cost isn't a problem, structured packing is likely to be used.

Actions:

1. To use structured packing in our DAC facility design.

Book: - Carbon dioxide pipelines: A preliminary review of design and risks

Carbon dioxide pipelines: A preliminary review of design and risks - ScienceDirect

Volume I, 2005, Pages 315-320} Relevant parts used from book.

Summary: *Provide a brief overview of this text.* This chapter in the book discusses that carbon dioxide pipelines can be safely constructed ensuring adequate risk assessment is conducted in both the design and operation. The paper also discusses the impact of carbon dioxide on the equipment selection and equipment design specific to the transportation and compression.
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. What causes the high amounts of corrosion in the pipeline? 2. What other features should the initial design consider? 3. What are the applications of thermal imaging in carbon dioxide pipelines? 4. What kind of safety reviews should be conducted? 5. What is pipeline control?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1.* The carbon dioxide will react with water to form carbonic acid. This is a major source of damage in pipelines. *2.* The initial design should include appropriate procedures for the abandonment of the pipeline and the prevention of use if the pipeline becomes damaged. List of pipeline engineering considerations: operating pressure; • operating temperature; • gas mixture composition; • corrosivity; • ambient temperatures; and • pipeline control (SCADA). *3.* Aerial pipeline surveys are a good way of checking pipelines as release of pressurized carbon dioxide results in a drop-in temperature. This allows thermal images to be obtained to detect releases. *4.* All equipment particularly if ordered in bulk must be checked for any defects and undergo sufficient quality checks to ensure that there is no malfunction in the equipment. The pipeline should undergo a HAZOP study (a structured and systematic technique for system examination and risk management). *5.* Pipeline control is a control system that monitors key parameters in real time. These parameters would include pressure, temperature and flow rate (others can include fatigue life and leak detection).
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* The safety features can be incorporated directly into the design in our project as the development of branch pipelines close to populated areas will result in an increased risk to the general public. The safety features will help to mitigate these risks.
Actions: How are you going to follow-up to progress your project work? 1. Use appropriate systems in our project to increase the safety of our DAC facility. 2. Research the corrosion resistance material properties of carbon steel (which is a common material in carbon dioxide pipelines due to its desirable properties).

Share this report with your team and discuss its findings.

Book: Carbon dioxide pipelines: A preliminary review of design and risks - ScienceDirect

Carbon dioxide pipelines: A preliminary review of design and risks

Summary: *Provide a brief overview of this text.* This text provides insight into the safety of constructing carbon dioxide pipelines and ensuring that adequate risk assessment is done during the design and operation. This is particularly important to the pipelines that have branch lines close to highly populated areas.
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. How safe is carbon dioxide pipeline? 2. How are gas leaks delt with? 3. What considerations need to be taken when implementing a pipeline? 4. What considerations need to be considered when implementing valves to the pipeline?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1.* Special design considerations need to be made when constructing facilities for pipelining carbon dioxide as there are serious hazards and risks of releasing carbon dioxide. *2.* Plants should have emergency response teams and operator testing for heavy hydrocarbons and carbon dioxide in low lying areas of the plant to detect high levels of carbon dioxide before they enter potentially dangerous areas. *3.* Risk assessment needs to be taken before to consider code and regulatory requirements. This would take into consideration: potential hazards (floods, erosion, seismic activity), leak detection, environmental requirements, operations and maintenance requirements. *4.* Having too many valves from the compressor to the storage point can cause problems. Even though having more valves allows for legs to isolated and vented these extra valves produce additional leakage paths. Pressure relief systems need to need to ensure extreme cooling does not take place during the pressure relief as this would cause damage to the valves. …
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* Design considerations can be used to produce safe pipelining. Risk assessment can be conducted to ensure that the local environment is suitable for pipelining.
Actions: How are you going to follow-up to progress your project work? 1. Need to conduct a risk assessment of the Guadalajara region to ensure it is safe to install carbon dioxide pipelines. 2. Estimate the required number of valves and ventilation system required to run pipelining.

Book Chapter: 23 - Carbon dioxide transportation Carbon Capture and Storage (Second Edition)

2017, Pages 595-611: [Carbon dioxide transportation - ScienceDirect]

Summary: *Provide a brief overview of this text.*

This book focuses on the transportation infrastructure that will be required to connect capture and storage sites for large scale development of DAC facilities. The chapters used focus particularly on the fundamental aspects of pipeline engineering for carbon dioxide transportation: flow in pipelines, material issues and product entry specifications.

Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.*

1. What calculations would be required to get values for fluid flow in the pipeline?
2. What is the advantage of having a subcooled liquid over supercritical fluid for dense phase transportation?
3. What is the general impact of impurities in the carbon dioxide on the transportation process?

Answers (knowledge): *Read the text more carefully and answer your questions.*

1.

Fluid flow

The pressure drop due to friction per unit length of pipeline, $\Delta p/\Delta L$ (Pa/m), depends on the diameter and internal roughness of the pipeline, the fluid flow rate, and the density and viscosity of the transported fluid, according to the Darcy–Weisbach equation:

$$\Delta p/\Delta L = f_D \rho u^2/2D \qquad (23.1)$$

where u is the fluid velocity (m^3/s), D is the pipeline diameter (m), ρ is the fluid density (~877 kg/m^3 for CO_2 at 11 MPa and 25°C), and f_D is the dimensionless Darcy friction factor. The Darcy friction factor depends on the Reynolds number (Re) and the surface roughness of the pipe (ε). The Reynolds number is defined as:

$$Re = 4\dot{m}/\mu\pi D \qquad (23.2)$$

where $\dot{m}$ is the mass flow rate (kg/s) and μ is the fluid viscosity (7.73×10^{-5} Pa s for CO_2 at 11 MPa and 25°C). For example, the flow in a 0.4 m diameter pipeline transporting 3.5 Mt-CO_2/year will have a Reynolds number of 4.5×10^6. The Darcy friction factor can be determined iteratively using the Colebrook–White equation:

$$f_D^{-1/2} = -2\log_{10}\left\{\varepsilon/3.7D + 2.51/Re\, f_D^{1/2}\right\} \qquad (23.3)$$

where the surface roughness ε is typically 4.6×10^{-5}m for commercial steel pipe. For the example used above, with Re~4.5×10^6, f_D will be ~0.014, giving an estimate of the pipeline pressure drop of ~15.2 Pa/m, or 1.5 MPa/100 km.

Figure 1. Screenshot of the relevant equations and definition of terms.

2. Supercritical fluid vs subcooled liquid depends on the temperature being above or below the critical temperature (31.1 degrees Celsius). Subcooled liquid has the advantage of higher density and lower compressibility allowing for smaller pipe diameters and lower pressure drops compared to supercritical fluid.
3. Trace quantities of impurities have no effect on the pipeline flow characteristics however, small amounts of hydrogen (even a few moles) results in a significant increase in the compression power requirements.

Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?*

The calculations to work out the fluid flow in the carbon dioxide pipeline can be used in the transportation section of our project.

Actions: How are you going to follow-up to progress your project work?

1. Research the best form of carbon dioxide for transportation in our situation and if the supercritical fluid or subcooled fluid method of dense phase transport would be applicable to Guadalajara.
2. Research a way to get an appropriate pipeline diameter.

Article: https://www.bbc.com/future/article/20210310-the-trillion-dollar-plan-to-capture-co2

The device that reverses CO2 emissions

Summary: *Provide a brief overview of this text.* The article provides an insight into a technology that is able to reverse carbon dioxide emissions by removing the gas from the atmosphere. It focuses on the importance of this technology and how it will be a step in the right direction in protecting the environment as thousands of DAC plants would be able to reverse the damage already caused to the environment.
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. What is the need to carbon capture technology? 2. How does the technology work? 3. Are there other technologies which can help reduce carbon dioxide levels in the atmosphere? 4. Will DAC technology be a permanent fix in reducing the enhanced greenhouse effect?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1.* There is a climate change problem caused by excess amounts of carbon dioxide in the atmosphere. With DAC any emission can be removed. This is better than having filters on emission sources as these cannot address the carbon dioxide already in the air. *2.* The system uses fans to draw in air containing carbon dioxide. Chemicals are used to absorb the carbon dioxide from the air. Further processes are done to produce pure carbon dioxide which is then stored. *3.* Other methods that can take carbon out of the atmosphere: restoring peatland and planting forests. However, these are slow processes and take up significant amounts of land which is extremely energy intensive on the environment. *4.* The DAC capture technology is likely to be a factor in the effort to reduce the enhanced greenhouse effect but the process isn't guaranteed to be successful. The technology is yet to be scaled up which could turn out less effective or more expensive than originally thought.
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* The fan technology and the chemical processes used to obtain the carbon dioxide can be used in our DAC facility.
Actions: How are you going to follow-up to progress your project work? 1. Article doesn't provide any insight into the storage, reuse, and transportation processes involved. Hence, further research would be required in these areas.

Journal Paper: Direct Air Capture of CO2: A Key Technology for Ambitious Climate Change Mitigation. Volume 3, Issue 9, 18 September 2019, Pages 2053-2057

Summary: *This Journal paper focuses on the effectiveness of direct air capture facilities and how realistic the technologies are at meeting global emission targets from the Paris agreement.*

Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.*

1. How effective are DAC facilities?
2. What are the different types of air capture facilities?
3. What can be done to minimise heat losses in a DAC facility?
4. Could DACs be a key technology for climate change mitigation?

Answers (knowledge): *Read the text more carefully and answer your questions.*

1. DAC could emerge as a key technology in carbon dioxide capture as their efficiency in extracting carbon dioxide is comparably high. However, full potential has not yet been realised due to high initial costs and energy input requirements.
2. The two main technology routes are high and low temperature desorption processes.
3. Possible to use lower temperature levels but this will be problematic for thermodynamic processes. Waste heat can be combined with power plants but a thermal energy buffer storage would be required.
4. Yes, but need to consider the high financial requirements (extremely expensive to remove carbon dioxide even on an annual basis).

Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?*

Further consideration needs to be taken in the storage, air capture and reuse of carbon dioxide in the DAC facility.

Actions: How are you going to follow-up to progress your project work?

1. Include further details on how efficient DAC facilities are and how much carbon dioxide can be removed per year to get a more accurate representation of the size of our DAC facility.
2. Need to decide on how reduce waste heat and find accurate ways to store and reuse the captured carbon dioxide.

Journal Paper: Carbon dioxide transport via pipelines: A systematic review - ScienceDirect

Carbon dioxide transport via pipelines: A systematic review

Summary: *Provide a brief overview of this text.* The journal focuses on the carbon dioxide pipeline technology and the design, construction and transport process.
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. What are the advantages and disadvantages of pipeline and tanker truck transport? 2. What factors determine the pipeline? 3. What form is the carbon dioxide in when being transported? 4. How to determine an appropriate pipeline diameter to transfer the required amount of carbon dioxide? 5. What methods would be required to maintain pressure in the pipeline? 6. What kind of terrain would affect the design of the pipelines? 7. What kind of safety and risks are associated with pipelines?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1.* Pipelines are preferred for large scale carbon capture and storage projects as they are key to the operation of a CCS operation, guarantee the safety of carbon dioxide in transport and guarantees the economic operation of the system. (Pros and cons of different transport systems provided in separate table). *2.* Transmission medium, operation and pipe material strength. Presence of impurities impact the transport of carbon dioxide. 3. The forms of carbon dioxide can be numerous. These include: gaseous transport, liquid transport, dense-phase transport, supercritical transport, and solid transport. Solid transport is not feasible. Short distance pipelines utilise gaseous transport and liquid transport. The remaining two can be used for long distance pipelines and are the most economical. 4. Formulas given in text with relevant references. The important take on this is to minimise the pipe diameter to meet the transportation requirements as a larger diameter significantly increases the initial investment. 5. For gas carbon dioxide compressors are used whereas for liquid or dense phase pumps are used. The preferred method for long distance pipeline is to use stepwise pressurization with multiple booster stations. 6. Areas with steep slopes and unstable soil layers need to be avoided (landslides). Pipelines also need avoid areas in seismic zones. 7. Accident rate of carbon dioxide pipeline is relatively low. If a leak occurs it will cause significant damage to the environment and can cause immediate death. However, this is highly regulated and unlikely to occur. Failure occurs in pipeline depending on the material being either too brittle or ductile. …
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* China is using a new method of transporting carbon dioxide onshore via highway cryogenic storage tanks. This could be beneficial to our DAC facility as pipelines can be difficult in situations with extreme environments. Also need to consider how much energy this process will take. Can utilise any of the formulas to get an accurate pipeline diameter.

IDP2 Research Journal Club Report

Actions: How are you going to follow-up to progress your project work?

1. Conduct further research into the transportation of carbon dioxide via highway cryogenic storage tanks.
2. Determine whether the environment of Guadalajara will allow for pipelines to transport the carbon dioxide to storage.
3. Research the carbon dioxide thermodynamic calculation and the state equation – which has significant influence on the design of the pipeline.
4. Research the areas in Guadalajara to ensure that the pipelines would be safe to operate in that area. If not other modes of transport will have to be used.
5. Research materials using CES Edupack to determine whether or not the material will fail.

Share this report with your team and discuss its findings.

Include this completed worksheet in your Assignment 1 report appendix.

Table 1. Table of multiple formulas which can be used to calculate the diameter of the pipeline.

Number	Equation	Reference(s)
1	$D =$ [illegible]	IEA GHG (2002)
2	$D =$ [illegible]	Hamelinck et al. (2002); Heddle et al., 2003
3	$D =$ [illegible]	Tian et al. (2017); GHG, 2005; Chandel et al. (2010)
4	$D =$ [illegible]	Zhang et al. (2006)
5	$D =$ [illegible]	Vandeginste and Piessens (2008)
6	$D =$ [illegible]	Vandeginste and Piessens (2008); McCoy and Rubin (2008); Mohitpour et al. (2003)
7	$D =$ [illegible]	Vandeginste and Piessens (2008)
8	$D =$ [illegible]	Chandel et al. (2010)
9	$D =$ [illegible]	Energy (2010)
10	$D =$ [illegible]	Tian et al. (2017)
11	$D =$ [illegible]	Johnson and Ogden (2010)

Note: D represents pipe diameter; f represents friction factor; L represents pipe length; p_1 represents inlet

Article citation: Selection of materials for high pressure CO2 transport - TWI (twi-global.com)

Summary: *Provide a brief overview of this text.* This paper explores the effect of material behaviour when in contact with high pressure carbon dioxide and he change in materials behaviour on the transport of carbon dioxide.
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. What materials are typical for transporting carbon dioxide? 2. What are the issues related to pipelines and corrosion? 3. How does the environment effect the material of the pipeline? 4. What is the weakest point of a pipeline?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1.* Typically, carbon steels and corrosion resistant alloys. Carbon steel is required for its high strength, toughness, and low permeability. Polymetric materials can be viable due to their high performance, but the interactions of impurities and polymers needs to be considered. *2.* Impurities (SOx, NOx, O2, H2S and H2O) in the carbon dioxide provide different corrosion behaviours which can be detrimental to the pipeline. The joints and welding structures in the pipeline are also weak points where corrosion can occur. The microstructure of the material is extremely import in providing carbon dioxide corrosion resistance. *3.* At low pH values high temperature values facilitate mass transfer processes causing corrosion however, this has the opposite effect at higher pH values. Increases in the partial pressure of carbon dioxide will increase the corrosion rate as this leads to an increase in the amount of carbonic acid. *4.* The weakest point is likely to be a weld or joint due to the corrosion they undergo and their susceptibility to failure.
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* Can include the effects of impurities in the pipeline and how this affects the design of the pipeline to transport the carbon dioxide.
Actions: How are you going to follow-up to progress your project work? 1. Use CES Edupack to research appropriate materials for the pipeline network for the DAC facility. 2. Research individual impurities and discover how the effect the corrosion in different materials.

Journal Paper / Book Chapter / Article citation: A. H. Alami et al. *Science of The Total Environment*(2021) - https://www.webofscience.com/wos/woscc/full-record/WOS:000605764100080

Summary: *Provide a brief overview of this text. Paper goes over how algae can be used to store algae and how algae can be used after as a source of biofuel*

Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.*

1. What process is needed to convert the algae to biofuel
2. What conditions are needed for optimum algae growth
3. How much CO2 can it absorb

Answers (knowledge): *Read the text more carefully and answer your questions.*

1. Growing, filtration, drying, refining, degumming, neutralizing, dewaxing, bleaching, deodorization.
2. Optimum pH: 7-9, temp: generally, between 20-30
3. 1.3-2.4 kg of CO2 per 1kg of algae
4. http://allaboutalgae.com/benefits/ - can be used for cosmetics, fertilizer, feedstock etc

...

Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?*

Have an algae farm attached to DAC facility to allow for instant CO2 use

The algae can be the used in lots of other industries to help reduce the amount of harmful chemicals that enter the world as well.

Actions: How are you going to follow-up to progress your project work?

1. Share idea of Algae farm with group to see if they agree with use of Algae farm
2. Research more into how the algae can be processed more efficiently and how it can be rescheduled.

Journal Paper / Book Chapter / Article citation: R. Pate, G. Klise, B. Wu *Applied Energy*(2011) - https://www-webofscience-com.ezproxye.bham.ac.uk/wos/woscc/full-record/WOS:000270913300007

Summary: *Provide a brief overview of this text.*

This article goes over the scale-up conditions for water, land and nutrients needed for a microalgal biomass farm. The biofuel considered in this article was neutral lipids as a high energy density feedstock for advanced biofuels

Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.*

1. How much fuel can be produced
2. How much algae will it produce
3. How much can it reduce greenhouse gas emissions if it replaces fuel
4. What is the productivity of the algae farm
5. How much can it reduce greenhouse gas emissions if it is used as a food source
6. How much space is needed
7.

Answers (knowledge): *Read the text more carefully and answer your questions.*

1. The plant they considered would be able to produce 214 kWh/season (1 season = 240 days)
2. 42.4 million kg dry / season
3. If 20% of algae oil used, will reduce transport emissions by 20%
4. If algae were processed and fermented into biofuel, could replace 26% of natural gas usage
5. Productivity of the farm is 20 g VS/m^2 per day
6. If all the algae were used as soybean food replacement, it would reduce GHG crop emissions by 17%
7. Space needed was 880 h or 8.8 square km
8.

...

Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?*

Actions: How are you going to follow-up to progress your project work?

1.

Journal Paper / Book Chapter / Article citation: Capturing CO2 from ambient air using a polyethyleneimine-silica adsorbent in fluidized beds https://www-webofscience-com.ezproxye.bham.ac.uk/wos/woscc/full-record/WOS:000340330500029 (from 2014)

Summary: *Provide a brief overview of this text.* Describes how Mesoporous silica-supported Polyethyleneimine (PEI)-silica and a capture system can capture CO2
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. How efficient is this method? 2. Is it cost effective? 3. What process is needed? 4. How much energy is needed for this process?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1. Nearly 100%* *2. Estimate running cost to be $108/t-CO2* *3. Uses circulating fluidized bed (CFB) absorber and Bubbling fluidized bed (BFB) reactor* *4. 6.6 GJ/t-CO2* …
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* *Can capture CO2 but don't know how to store*
Actions: How are you going to follow-up to progress your project work? 1. Research about Guadalajara 2. See if there is way to separate the CO2 from the silica if not done already

Journal Paper / Book Chapter / Article citation: J. Zong, L. Sun, W. Bao
IOP Conference Series: Earth and Environmental Science(2020) - https://www-webofscience-com.ezproxye.bham.ac.uk/wos/woscc/full-record/WOS:000615964600089

Summary: *Provide a brief overview of this text.*
Paper illustrates main links of CCUS process and intros storage methods

Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.*

1. What methods are there to capture?
2. What methods are there to transport?
3. What methods are there to utilise?
4. How can CO2 be stored?
5.

Answers (knowledge): *Read the text more carefully and answer your questions.*

1. The carbon capture process includes: oxy-fuel combustion capture, post-combustion capture, pre-combustion capture, and physical absorption process.
2. *Usually pipelines or trucks, trains, or ships*
3. *carbon dioxide-EOR technology and carbon dioxide-ECBM*
4. *Usually involves injecting CO2 into deep geological structures*
   These places are depleted oil and gas reservoirs, deep saline aquifer, coalbed storage

...

Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?*
Uses one of the storage methods i.e oil reservoir or coalbed storage
Lots of capture methods however need to decide on which one to choose that best suits area
Not much on how CO2 can be utilized, so cannot comment on that from this article

Actions: How are you going to follow-up to progress your project work?

1. Research more on identified areas and see if they relate to Guadalajara
2. Research the Area of Guadalajara and surrounding areas to see if any places can be used for storage
3. Research more into how CO2 can be utilized and reused

Share this report with your team and discuss its findings

Journal Paper / Book Chapter / Article citation: Herzog, Howard J.. Carbon Capture, MIT Press, 2018. ProQuest Ebook Central, https://ebookcentral.proquest.com/lib/bham/detail.action?docID=5496104. – chapter 4

Summary: *Provide a brief overview of this text. Chapter explains ways that captured carbon can be stored or reused in different industries*
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. What ways can carbon be used after being captured? 2. How much carbon is currently reused? 3. How useful is it to reuse carbon 4. How much carbon can be reused 5. How much energy is needed to reuse the carbon
Answers (knowledge): *Read the text more carefully and answer your questions.* *1. Can be recycled back to fuel. Some building materials, carbonated beverages, flash freezing food, for fire extinguisher* *2. Only less than 1%* *3. Can be useful as can be turned into energy, keeps food fresh but at the moment, it isn't as useful as it could be* *4. At best, all of it (40Gt each year from energy use)* *5. fuel - requires 1.3-1.5 units of energy to get 1 unit of energy back, i.e not worth it* …
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* *Looking at ways that the carbon can be reused, ie selling it to food, drinks and building material companies. However, not many ways have been stated on how to reuse carbon*
Actions: How are you going to follow-up to progress your project work? 1. Research more into how carbon can be reused instead of stored and see if there are any newer ways that CO2 can be converted into energy again 2.

Journal Paper / Book Chapter / Article citation: L. Pires Da Mata Costa et al. *Processes*(2021) - https://www-webofscience-com.ezproxye.bham.ac.uk/wos/woscc/full-record/WOS:000654490600001 pages 35-54

Summary: *Provide a brief overview of this text. Chapter explains ways that captured carbon can be stored or reused in different industries – Explains current methods of CO2 utilization and how these are done*
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. Methods of carbon utilization? 2. Energy needed for processes 3. Are the processes feasible?
Answers (knowledge): *Read the text more carefully and answer your questions.* 1. Can be used to manufacture many materials, can be converted into valuable chemicals eg methane, methanol, ethanol etc, CO2 bioconversion, Polymer synthesis, Dry reforming of methane, Oxidative dehydrogenation of light alkanes to alkenes, photo-electrocatalysis, electrochemical cells 2. Unfortunately, the paper doesn't say how much energy is needed for the process 3. CO2 bioconversion now needs development to be economically feasible – but is expected to become competitive in medium/long term ...
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* *Can use some of these processes to use up some of the stored CO2 to e.g create energy, plastics or valuable gases, this can be either at the DAC facility or the CO2 transported to a plant to be processed into the necessary products*
Actions: How are you going to follow-up to progress your project work? 1. Look into what would be most suitable to be included in the project/facility 2. Look into other ways the CO2 can be reused. 3. Look into the processing needed to reuse the CO2 before it can be processed into new materials/chemicals

Journal Paper / Book Chapter / Article citation: G. Centi, G. Iaquaniello, S. Perathoner *ChemSusChem*(2011) - https://www-webofscience-com.ezproxye.bham.ac.uk/wos/woscc/full-record/WOS:000295257500007

Summary: *Provide a brief overview of this text. This article goes over some ways that CO2 is utilized and how useful it could be in the future*

Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.*

1. Ways CO2 is used
2. Energy needed for the processes

Answers (knowledge): *Read the text more carefully and answer your questions.*

1. As renewable energy storage for use and transport, to produce ethylene and propylene, help make renewable H2.
2. Renewable energy storage – Unsure but can be used to make chains to make CO2 derived products such as methanol and longer-carbon-chain alcohols and hydrocarbons.

...

Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?*

Still haven't got energy costs for each process, these processes will hopefully be largely updated when facility is running so CO2 can be transported to other places to be used

Assumption that the CO2 used was in gas form so would have to be transported in canisters/ containers

Actions: How are you going to follow-up to progress your project work?

1. Look into which again will be mostly likely to be used in the future and if the reuse facility should be connected to the DAC facility.

Journal Paper / Book Chapter / Article citation: Jung, J.Y., Huh, C., Kang, S.G., Seo, Y. and Chang, D., 2013. CO2 transport strategy and its cost estimation for the offshore CCS in Korea. *Applied energy*, *111*, pp.1054-1060.

Summary: *Provide a brief overview of this text.* Looks into CO2 transport and storage offshore, focusing on infrastructure.
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. What are the 3 segments for the ship-based Korean CCS chain? 2. What does the liquefaction system consist of?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1.* In-land transportation, liquefaction barge and marine transportation. CO2 at the power plant is first compressed by the compressor, then transported to the barge via a pipeline. The liquefaction system liquefies the transported CO2 as the density of vapor CO2 is too low for economic transportation. This is temporarily stored in storage tanks until the CO2 carrier comes for loading. The stored CO2 is unloaded into the carrier via the cargo handling system, & then the carrier goes to the geological storage site, where CO2 is finally injected. *2.* Propane-ethane cascade cycle is used as the liquefaction process due to its high efficiency. It consists of compressors, heat exchangers & scrubbers.
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* Insight into the process of how CO2 is transported and temporarily stored, and later on stored underground (offshore in this case).
Actions: How are you going to follow-up to progress your project work? 1. Find more information on the liquefaction process, particularly the propane-ethane cycle, and compare it to other methods to see which is truly the best method for liquefying CO2. 2. Look into temporary storage tanks for liquid CO2. 3. Find more general cases for CO2 temporary storage that can later be used to be stored underground, as this article is only specific for the storage sites in Korea.

Journal Paper / Book Chapter / Article citation: Singh, R.N. and Sharma, S., 2012. Development of suitable photobioreactor for algae production–A review. *Renewable and Sustainable Energy Reviews*, *16*(4), pp.2347-2353.

Summary: *Provide a brief overview of this text.* Goes through the photobioreactors used to deal with microalgae growth, discussing their designs, advantages & disadvantages.
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. How do you cultivate algae? 2. What are the pros and cons of using open systems? 3. How are closed pond systems better than open pond systems? 4. What are photobioreactors & why are they favoured compared to open systems? 5. What general problems are associated with photobioreactors? 6. What types of photobioreactors are there?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1.* You can cultivate algae in open systems such as lakes or ponds, or in controlled closed systems such as photobioreactors (PBR). *2.* Open pond systems in lakes, lagoons or ponds are cheaper to construct, have the largest production capacities compared to other systems, certain algae species can exploit certain conditions such as salty water, low production & operating costs. However, they're vulnerable to contamination from the outside environment by other algal species or bacteria. These systems don't offer control over temperature nor lighting, bad weather and certain seasons can stunt algal growth, ponds are subject to uneven light intensity, evaporative losses (e.g. diffusion of CO2 to the atmosphere), and take up a lot of land. There aren't very efficient mixing mechanisms in these open systems, so mass transfer rates are poor which leads to low biomass productivity. *3.* Limitations of an open pond system can be overcome by closing ponds using a transparent/translucent barrier, using plexiglass, turning it into a greenhouse. This allows for more biomass growth, ability to be heated, increase the amount of CO2 present and so leading to increase in algal growth. *4.* They're enclosed illuminated vessels made for controlled biomass production. Their enclosures means there's no contamination from the outside environment and less CO2 loss and prevention of water evaporation, and allows better control over pH, temperature, light, CO2 concentration conditions, etc., allows for higher cell concentrations. *5.* Microalgae is very adhesive leading to rapid fouling of light transmitting surfaces of reactors, leading to frequent shutdown of reactors for mechanical cleaning & sterilization. Therefore, the photobioreactor design must prevent or minimize the effect of fouling. *6.* Vertical tubular (bubble or airlift column), flat panel, horizontal tubular, helical type, stirred tank, hybrid type, etc. Bubble column bioreactors have low capital costs, high surface area to volume ratio, lack of moving parts, satisfactory heat & mass transfer & efficient release of oxygen & residual gas mixture. Modified flat panel bioreactors have highest productivity under over saturating light conditions. (1.7x higher volumetric mass productivity than a bubble column reactor). Horizontal tubular bioreactors are advantageous outside due to their orientation towards the sun, with better photosynthetic efficiency & volumetric mass productivity than a flat panel bioreactor. Hybrid reactors are proven to be better than single bioreactors for culturing algae.

Journal Paper / Book Chapter / Article citation: Iancu, P., Plesu, V. and Velea, S., 2012. Flue gas CO2 capture by microalgae in photobioreactor: a sustainable technology. In *15th Conference on Process Integration, Modelling and Optimization for Energy Saving and Pollution Reduction. Prague.*

Summary: *Provide a brief overview of this text.*
A short paper discussing technology development involving the use of microalgae to capture CO2 from power plant flue gas in alkaline conditions, which later on can be used to produce biodiesel from algal oil.

Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.*

1. What were the algae candidates to be used in the laboratory experiment, and which one was used & why?
2. What does the algae cultivation pilot plant capture CO2?
3. What is the entire process from start to finish?
4. What are the materials involved in the process?
5. What were the annual costs for each of the 3 sections of the photobiocapture pilot technology?
6. What are the environmental impact effects for these 3 sections?
7. What does the paper conclude?

Answers (knowledge): *Read the text more carefully and answer your questions.*

1. There were 3 candidate microalgal species, Chlorella homosphaera, Chlorobotrys simplex, Scenedesmus opolienis – the last was used, as out of the 3 species it was the most vigorously growing with optimal cell growth, higher photosynthetic efficiency, larger biomass & algal oil production.
2. The plant captures CO2 from industrial flue gas.

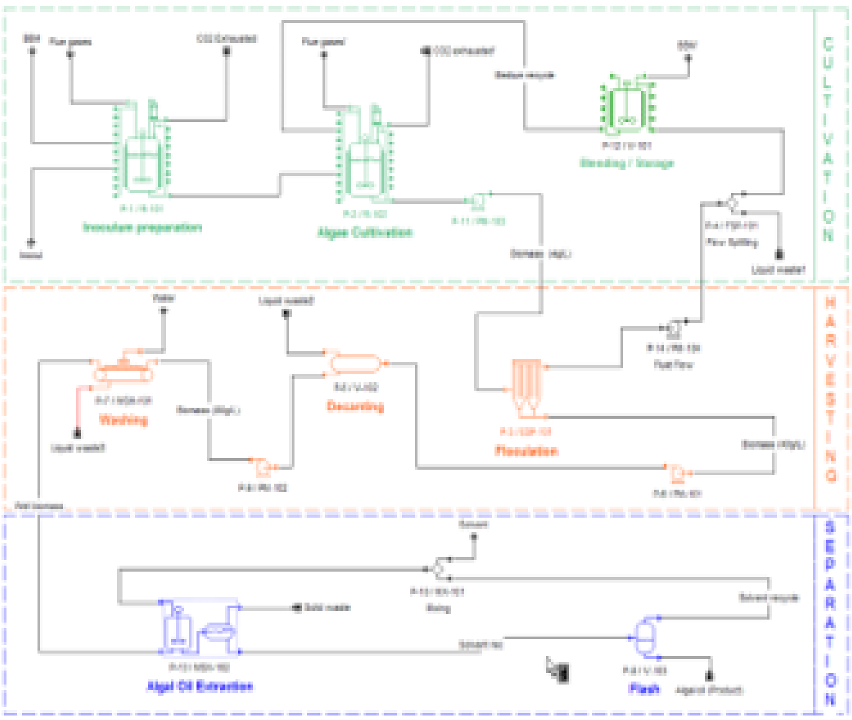


Figure 2: CO_2 photobiocapture pilot technology flowsheet

3. Biomass is cultivated in a semi-batch operated laboratory scale photobioreactor BIOSTAT PBR 2S Sartorius (operating conditions: suspension volume 3L; temperature 28 degrees Celsius; light intensity 240 µE/m^2 s; flue gas composition was 7% CO_2, 14% O_2 & 79% N_2 at 20 mL/min). To reduce energy consumption, electro flocculation is done. 80%-95% of microalgae is separated, and suspended biomass is collected continuously (~300 mL/d, i.e. 10-12 mL/h), flocculated, and then filtered/washed with distilled water to remove remaining salts & nutrient medium. Lipids are finally extracted (18g, i.e. <45% of dry biomass) using $CHCL_3$ from 80% moisture biomass. Figure 2 shows the flowsheet for the entire process.

4. The process is split into 3 sections: algae cultivation, biomass harvesting, algal oil extraction. Algae culture involved medium nutrient (Bold Basal Medium – BBM), inoculum, flue gases, biomass suspension, liquid waste. Biomass harvesting involves biomass suspension, water wash & liquid waste. Algal-oil extraction involves biomass suspension, solvent, algal cake & algal oil (the final product). Experimental and simulation results can be found in Table 2.

Table 2 Overall mass balance per batch

Section	Material	Experimental (g/batch)		Simulation (kg/batch)	
		IN	OUT	IN	OUT
Algae culture (Biomass – 4g/L)	Medium nutrient (BBM)	11,700	-	7,200	-
	Inoculum	300	-	300	-
	Flue gases	1,200	1,100	1,200	1,207
	Biomass suspension	-	1,200	-	1,200
	Liquid waste	-	10,900	-	6,293
Total Algae cultivation Section		**13,200**	**13,200**	**8,700**	**8,700**
Biomass Harvesting (Biomass- 80g/L)	Biomass suspension	1,200	225	1,200	225
	Water wash	100	-	100	
	Liquid waste		1,075	-	1,075
Total Biomass harvesting Section		**1,300**	**1,300**	**1,300**	**1,300**
Algal-oil Extraction	Biomass suspension	225	-	225	-
	Solvent	85	-	83	-
	Algal cake	-	292	-	290
	Algal oil (Product)	-	18	-	18
Total Algal oil extraction Section		**310**	**310**	**308**	**308**

5. Production costs of algal biomass grown in photoreactors can range from 2.85 US$/kg to 30-70 US$/kg, depending on the climate, species used, growing systems & other conditions. Algal oil cost can range from 2.8 – 352 US$/L. Figure 3 illustrates annualised costs for algal oil production, where 65% of product cost is allocated to algae cultivation, 18.5% to harvesting & 16.5% to algal oil separation. The total production cost for the pilot plant capturing ~1,400 kg CO_2/y, & producing ~200kg of algal oil/y is ~24,600 euros/year.

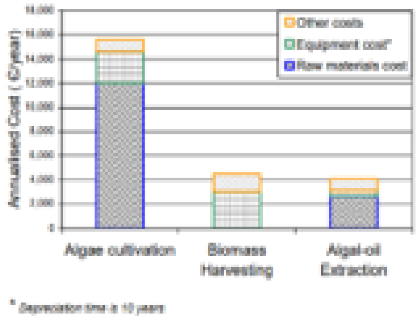


Figure 3 Annualised costs for algal oil production

Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?*

Paper provides a flowsheet that can be helpful to find the components used for CO_2 being captured via algae. Also provides numerical values that can be used to justify use and to be mentioned in the report & presentation.

Actions: How are you going to follow-up to progress your project work?

1. Research the other 2 microalgal candidates to see why they weren't selected.
2. Find out how each components shown on the flowsheet work, which will help in the design stage.
3. As there probably won't be an industrial plant on site, calculations will need to be done to for an alternative stream of CO_2 from the DAC facility, which would compose of a lower percentage of CO_2, compared to flue gas.

Journal Paper / Book Chapter / Article citation: Razzak, S.A., Hossain, M.M., Lucky, R.A., Bassi, A.S. and De Lasa, H., 2013. Integrated CO2 capture, wastewater treatment and biofuel production by microalgae culturing—a review. *Renewable and sustainable energy reviews*, *27*, pp.627-630.

Summary: *Provide a brief overview of this text.* Looks at the different types of closed systems for microalgae cultivation, listing advantages & disadvantages.
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. What are the types photobioreactors and explain how they work? 2. What are the advantages of each photobioreactor? 3. What are the disadvantages of each photobioreactor?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1.* Tubular, plastic bag, airlift, flat plate photobioreactors. Tubular photobioreactors have a gas exchange vessel, where air CO2 & nutrients are added & oxygen is removed, is connected to the main reactor. The medium is circulated through the tubes, exposed to sunlight for photosynthesis, back to a reservoir with the help of a mechanical/airlift pump. The pump helps maintains a turbulent flow to prevent algal biomass from settling. Fractions of algae is harvested after it circulates through the solar collection tubes. Plastic bag photobioreactors have microalgae cultivated in transparent polyethylene bags, which are hung or placed in a cage under sunlight irradiation. The cultures are mixed with air at the bottom, where there're sealed transparent polyethylene sleeves in a conical shape to prevent cell settling. Airlift photobioreactors have vessels divided into 2 interconnected via a baffle/draft tube. Liquid moves in a large circular motion, cycling between irradiated & dark zones. Flat plate photobioreactors, mixed by air bubbling seem to be better versions than bubble column (vertical tubular) photobioreactors. 2. Tubular photobioreactors have a large surface area per unit volume, for maximum sunlight exposure for microalgae. Airlift photobioreactors allow microalgae to go through light/dark cycles thanks to the circular flow of fluid. They have high mass transfers, good mixing with low shear stress, low energy consumption, easy to work with, good for preventing algae from settling, cultures suffer less from photo-inhibition & photo oxidation. Flat plate bioreactors are easier to operate. They have a large irradiated surface area, suitable for outdoor cultures, good for algae immobilization & biomass productivities. They're relatively cheap and easy to clean. They have large volume capacity units that can be used for several days, making them fully scalable units. 3. Tubular photobioreactors are challenging to scale up. Some systems such as helical-tubular photobioreactors (tubes are coiled spirals) require artificial illumination alongside natural light to enhance microalgae growth, but this adds to production costs. Airlift photobioreactors have a low surface/volume ratio, higher manufacturing & maintenance cost, smaller irradiation per unit surface area, more sophisticated construction materials, higher shear stress on algal cultures. They are also difficult to scale-up given their complex flow pattern, so more units are needed to build a commercial plant. Flat plate photobioreactors have difficulties in controlling culture temperature, limited degree of grow that the near wall region, potential of hydrodynamic stress which algal strains will be subject to, photo-inhibition can occur.
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* Gives the advantages & disadvantages for each photobioreactor, and whether or not they can be commercially scaled up.
Actions: How are you going to follow-up to progress your project work? 1. Do more research to see which photobioreactor out of the 4 is better. 2. Find out the components that make up each photobioreactor.

Journal Paper / Book Chapter / Article citation: Vasumathi, K.K., Premalatha, M. and Subramanian, P., 2012. Parameters influencing the design of photobioreactor for the growth of microalgae. *Renewable and Sustainable Energy Reviews*, *16*(7), pp.5443-5450.

Summary: *Provide a brief overview of this text.* Goes through the factors that influence the growth of microalgae used in photobioreactors.
Questions (aims): 1. What are the essentials requirements to grow microalgae? 2. How can CO2 be absorbed by algae, and name any pros or cons associated with these methods? 3. What is fixation? 4. For light, nutrients, and microalgae concentration, what needs particular attention? 5. What are the features included in a photobioreactor that's economically viable?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1.* CO2, light, nutrients, & microalgae concentration. *2.* 2 ways CO2 can be absorbed by the microalgae is via mass transfer or chemical reaction. Mass transfer limitations can slow down microalgae growth, so area of contact & mixing will reduce this mass transfer resistance. This can be further reduced by giving a desired CO2 concentration, microalgae & dosage of light irradiance for bio-fixation reaction at the site of reaction with microalgae. Directly bubbling (passing CO2 through a sparger in water) or absorption in packed bed can help increase surface area (however, bubbling uses more energy and can cause algal cell damage, and packed beds uses more energy).Thin layer culture technology can be used to provide large surface area to support high mass transfer rate. For chemical reactions, CO2 can be absorbed in alkaline solutions, increasing solubility of CO2 and so more CO2 availability, but this method makes the variety of microalgae species used limited. It's concluded that chemical reactions are the better method to absorb CO2. *3.* Uptake of CO2 by microalgae for its growth. 1g of dried microalgae would require 1.65-1.83g worth of CO2. Increasing CO2 fixation requires increase in CO2 residence time in bioreactors. The absorption rate of CO2 should be more or less the same as that of fixation rate (growth rate of microalgae, which depends on temperature & number of available photons required by microalgae). *4.* For light, a given photon flux density (PFD) is needed (not too high or it'll cause photo damage & so reduce photosynthetic capacity). Dark time is needed to repair photo induced damage, so a light/dark cycle in the range of 10-100s, with the dark period being up to ~20% of the cycle time. Optimum levels of microalgae population density is needed to achieve higher photosynthetic rate. Microalgae should be limited to up to a depth of 15cm, or else there'll be stronger photo limitation & inhibition at these depths. Bioreactors can achieve high photosynthetic rates, as long as the layer of microalgae is only a few mm up, with a harvesting density >30g DW/L. For nutrients, sufficient nutrient medium should be provided & maintained equating the amount of nutrient consumed by harvest algae. For microalgae concentration, the population density must be maintained at its optimum concentration by harvesting excess microalgae formed, in order to achieve highest rate of microalgae growth. *5.* Highest surface area/volume ratio; stabilizing absorbed CO2; providing sufficient time for photon absorption; maintaining optimum concentration of microalgae; maintaining desired level of nutrients – however there're no widely used photobioreactors that meet all of these criteria, so to make sure the photobioreactor's economically viable, it must use suitable species with high growth rate, high CO2 fixation rate, low contamination risk, low operation cost, easy to harvest, & rich in valuable components in their biomass for reuse.
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* Learnt the parameters that affect microalgae growth, which will influence the design for the project.
Actions: How are you going to follow-up to progress your project work? 1. Find the best suitable photobioreactors that's economically viable for the project. 2. See if there're other essential factors that can affect microalgae growth.

Journal Paper / Book Chapter / Article citation: Savage, N., 2011. Algae: the scum solution. *Nature*, *474*(7352), pp.S15-S16.

Summary: *Provide a brief overview of this text.*
An article talking about the potential of using algae as biofuel, and the problems of producing biofuels regarding space and efficiencies.

Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.*

1. How does a closed photoreactor work?
2. What are the pros with photoreactors?
3. What are the problems with photoreactors?
4. How can algae growth be made better?

Answers (knowledge): *Read the text more carefully and answer your questions.*

1. There are an array of glass tubes where CO2 circulates through a mix of algae & water, where the tubes are exposed to sunlight.
2. Photoreactors take up less space than open ponds, by using an array of glass tubes. They're stacked in layers for better sunlight exposure.
3. As the reactors absorb sunlight, they heat up, so they require cooling such as spraying water on the tubes, which may mean the savings on evaporative loss are gone. These photoreactors also need CO2, but getting it from the atmosphere isn't enough for rapid growth on a commercial scale, meaning it'll need to retrieve the CO2 from artificial sources such as coal-power plants, and transporting CO2 >4-5 miles will lead to high piping costs.
4. Adding more nutrients to the organisms will lead to more growth, but less oil production, making it more efficient when taking out CO2 and storing it. Blue-green algae (more of a bacteria of the genus Cyanobacterium), secrete oil instead of being destroyed to retrieve the oil, meaning continuous production is possible as you don't have to kill a batch of algae and grow more. In the future, editing the genes of cyanobacteria can lead to better abilities for the organisms to retrieve CO2 from the atmosphere.

Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?*
Better understanding of photoreactors of their use regarding CO2 storage.

Actions: How are you going to follow-up to progress your project work?

1. See whether or not techniques made to grow algae faster can be applied to photoreactors.
2. Find the best algae type to use for photoreactors.

Journal Paper / Book Chapter / Article citation: Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (2019) Chapter: 5 Direct Air Capture
https://www.ncbi.nlm.nih.gov/books/NBK541435/

Summary: *Provide a brief overview of this text.*
The chapter looks into capturing CO2 using either liquid solvents or solid sorbents, and compares them via annual CO2 reduction potential, cost, and capacity. At the time of writing, the author states that neither of the 2 methods are leading.

Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.*

1. What's the most common carbon capture method companies are using in their upcoming DAC systems?
2. What's the most common method companies are using to release captured CO2, so that the carbon capture methods can be done continuously?
3. Which carbon capture method has the most positive impact on climate change, and why?
4. How can a DAC plant be powered?
5. What determines how much land is required for the DAC plant?
6. What environmental impacts do DAC plants have?

Answers (knowledge): *Read the text more carefully and answer your questions.*

1. Solid sorbents were more commonly used to capture CO2 (4 out of 5 companies).
2. Heating, or a combination of both heat and a vacuum (only 1 company used humidity for solid sorbent regeneration).
3. Solid sorbents, as they require lower temperatures for regeneration compared to liquid solvents (<150 degrees Celsius compared to 900 degrees Celsius respectively), and so it means less energy is used to provide heat & power to operate the system, so the ratio of CO2 emitted per CO2 captured is lower.
4. If using liquid solvents to capture CO2, then fossil fuels such as natural gas and coal will be needed to power the plant, but if using solid sorbents, then you can use solar energy using concentrated solar power towers, low-carbon hydrogen combustion, photovoltaic (PV) or wind-powered electric heating, or alternative designed nuclear reactors (e.g. high-temperature gas-cooled reactors).
5. Contactors are what determine how much land is needed for the DAC plant; local power islands may also take up land onsite, such as a natural gas plant (~30 acres), concentrated solar thermal (3 acres GWh^-1yr^-1), small 2-axis flat panel PV power plant (5.5 acres GWH^-1yr^-1) or even turbines (40+-25 acres GWH^-1yr^-1), etc.
6. Capturing CO2 will deprive algae cultures, crops, and local habitats of CO2; solid waste produced from liquid solvent systems can impact the environment if led to build up and not taken care of.

Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?*
Perhaps best to design a solid sorbent system for the DAC facility, as renewable energy can be used to power the plant, so costs are lower, and impact on climate change is positive. A solar powered energy facility will look more appealing than say a coal or natural gas plant, and can take advantage of the Mexican tropical weather.

Actions: How are you going to follow-up to progress your project work?

1. Look up emerging technologies to see which could make 1 of the 2 capture methods more leading than the other.
2. Look up the developments of DAC facilities utilising solid sorbent systems from the 5 companies, to see more in detail how they capture the CO2, and what components the facility has in order to complete this process, and how much land it'll all take.

Journal Paper / Book Chapter / Article citation: Rackley, S. A. (2017). Carbon capture and storage Chapter 1 - Introduction. Butterworth-Heinemann. https://www-sciencedirect-com.ezproxyd.bham.ac.uk/book/9780128120415/carbon-capture-andstorage

Summary: *Provide a brief overview of this text.* This chapter goes through the history of CO2 emissions up to now, and the importance of tackling global emissions with the help of carbon capture & storage (CCS). It discusses inventories & fluxes that make up the global carbon cycle, and goes through the process of technological innovation for CCS projects to go commercial.
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. What are the carbon inventories in the carbon cycle? 2. How much do these carbon inventories hold? 3. What are the fluxes in the carbon cycle? 4. What factors will have an effect on future levels of anthropogenic CO2 emissions. 5. What is the target COP15 put to tackle climate change? 6. What objective do CCS projects have?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1.* Atmosphere; Surface & deep ocean; marine biota; fossil fuels & marine sediments; lithosphere; vegetation & soils. *2.* Volcanism; land use change; rivers; sediments; fossil fuels. *3.* Sedimentary rocks in the lithosphere holds ~5x10^7 Gt-C (fossil fuels hold 8000-10000 Gt-C); the ocean holds~39,000 Gt-C; marine carbonate sediments hold 2500 Gt-C; the terrestrial terrain holds ~2600 Gt-C (600 Gt-C as living biomass, & the rest as organic carbon in soils & sediments to 2m depth); the atmosphere holds ~850 Gt-C (annual increase of ~4 Gt-C/year). *4.* Population & economic growth, trade globalization, energy intensity of industrial product; use of fossil fuels for energy; technological advancements in the energy industry, politics revolving around the environment. *5.* Global temperatures cannot increase by more than 2 degrees Celsius before 2100. *6.* Current & future CCS projects should capture & store 20 Gt-C by 2050.
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* Future projections of global temperatures at the current rate isn't good, and so it's best to develop a DAC facility to make sure it achieves NET status. Use technology in the designed DAC facility that is cheaper, in order to incentivise investors to fund the project.
Actions: How are you going to follow-up to progress your project work? 1. Find more CCS projects to see their RDD&D timelines for a better understanding of RDD&D in CCS. 2. Research emerging technologies that can make future CCS projects cheaper to develop, as cost can prevent/delay progress of meeting the global temperatures target.

Journal Paper / Book Chapter / Article citation: Rackley, S. A. (2017). Carbon capture and storage Chapter 2 – Overview of carbon capture & storage. Butterworth-Heinemann. https://www-sciencedirect-com.ezproxyd.bham.ac.uk/book/9780128120415/carbon-capture-andstorage

Summary: *Provide a brief overview of this text.* Chapter goes into current & emerging technologies for carbon capture & storage (CCS).
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. What are the 3 ways to capture CO2? 2. What are the pros to direct air capture (DAC)? 3. What are the cons to DAC? 4. How can CO2 be stored?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1.* You can capture CO2 from an existing (or adjusted) industrial process or from the discharge of an industrial process, or from power generation, or via DAC which is what we're focusing on. *2.* Uses just about the same energy as capturing from a flue gas stream (difference is 15 kJ/mol), however it can be lower as the use of amine solvents in DAC systems require lower temperatures; DAC can be a negative emissions technology (NET), whereas other capture systems only reduce CO2 emissions; injection into oil & gas reservoirs can bring economical advantages as it can enhance hydrocarbon recovery. *3.* Captures CO2 from ambient air which has a concentration of 0.04% (in comparison to 30% from cement plants); DACs can be expensive to research & develop compared to other capture systems. *4.* Injecting CO2 into oil, gas, & water-bearing geological formations (only option that's been done commercially) – they can be stored in oil & gas reservoirs, or in non-potable water; CO2 can also be injected deep under the ocean; into terrestrial ecosystems; by mineral carbonation; as an industrial feedstock.
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* Discusses ways to discuss storage options for CO2 capture, which is useful for the project. The project would need to tackle energy problems (i.e. not using non-renewable energy sources to power the plant), to make sure it becomes a NET.
Actions: How are you going to follow-up to progress your project work? 1. Look into other ways of storing CO2, and find out why they're not used (such as ocean storage), or if there're new emerging technologies that can replace the commercial way of storing CO2. 2. Find types of energy resources (probably renewable sources) that can be used to power the DAC facility whilst making sure it stays a NET.

Journal Paper / Book Chapter / Article citation: Rackley, S. A. (2017). Carbon capture and storage Chapter 11 – Introduction to geological storage. Butterworth-Heinemann. https://www-sciencedirect-com.ezproxyd.bham.ac.uk/book/9780128120415/carbon-capture-andstorage

Summary: *Provide a brief overview of this text.* Goes over the many ways on how CO2 can be stored into subsurface rock formations, and the potentials and limitations that they have.
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. What are the subsurface storage options? 2. What are the types of trapping mechanisms? 3. What are the pros &/or cons to these trapping mechanisms? 4. What are the limiting factors that affect geological storage capacity?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1.* Saline aquifer storage (injecting aquifers not used for drinking water); enhanced oil/gas/coal bed methane/geothermal recovery (EOR – injecting oil fields; EGR – injecting gas fields; ECB – injecting un-mineable coal seams ;EGS - using CO2 as a fluid in geothermal energy extraction & energy systems); compressed air energy storage systems (CAES – CO2 as a cushion gas to store energy from intermittent sources); in situ mineral carbonation (inject of CO2 into fractured alkali mineral deposits, and storage via mineral carbonation). *2.* Structural & stratigraphic trapping (impermeable barrier or caprock blocks upward movement of CO2); residual trapping (plume of CO2 rising through a water-saturated formation will lead to water being drawn into pores via capillary imbibition, reducing permeability of the rock, and reducing CO2 to a residual saturation); solubility trapping (dissolution of CO2 in a saline aquifer); ionic trapping (CO2 dissolves in formation brine to form carbonic acid, where successive deprotonations produces bicarbonate ions and then the carbonate ion); mineral trapping (reaction of dissolved CO2 with Ca, Fe or Mg containing minerals in the rock matrix leads to precipitation of carbonates in the pore spaces). *3.* Structural & stratigraphic trapping CO2 has the highest risk of leakage for OC2, as fluid's mobile and can migrate through compromised material; residual trapping has a very low risk of leakage, and CO2 will eventually dissolve in the formation brine & mix with the surrounding unsaturated aquifer; solubility trapping is effective on a centennial time scale, and can be done quicker via special injection strategies (or if the aquifer's hydrodynamically active); ionic trapping can lead to mineral trapping; mineral trapping is the most stable out of all the mechanisms, however is the slowest trapping process (operation on a millennial time scale). *4.* Geo-mechanical (maximum pressure increase allowed without geo-mechanical failure of the rock); fluid flow (vertical permeability and reservoir heterogeneity can affect the migrating plume which expels gross volume where residual trapping occurs); rock – fluid interactions (residual saturation of CO2 is influenced by the maximum injection rate); fluid – fluid interactions (pore space occupied by irreducible formation brine can become available for structural trapping); hydrological (maximum pressure increase without adverse impact on potable water sources); operational – pressure management (techniques can be done to mitigate pore pressure increase, and remove/relax the geo-mechanical limit); policy constraints (regulations could limit the extent of how much a storage capacity can be fully utilized).
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* Injection into saline aquifers and oil reservoirs are widely available, making them a useful option to store CO2 (only options done on a large commercial scale).
Actions: How are you going to follow-up to progress your project work? 1. Look into the progress and conclusions of any existing demonstrations of any CCS projects that utilise any form of CO2 geological storage. 2. Look into long-term effects of storing CO2 with each of these methods.

Journal Paper / Book Chapter / Article citation: Rackley, S. A. (2017). Carbon capture and storage Chapter 20 – Ocean storage. Butterworth-Heinemann. https://www-sciencedirect-com.ezproxyd.bham.ac.uk/book/9780128120415/carbon-capture-andstorage

Summary: *Provide a brief overview of this text.* Chapter looks into the various ways of storing CO_2 into the oceans and thereby increasing the oceanic inventory.
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. What properties of the seawater will affect the behaviour of CO_2? 2. What are the 2 direct methods of storing CO_2 into the oceans? 3. Are there any other alternatives to storing CO_2 into the oceans?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1.* The pressure of the water (this will determine CO_2s buoyancy, and, if it reaches the liquefaction pressure at a given temperature, CO_2 will liquefy, form & decompose). *2.* Direct CO_2 dissolution – releasing CO_2 at depths >500m would liquefy CO_2, and form a hydrate shell around the individual liquid droplets (if above ~2500m, depending on the droplet size & hydrate skin thickness, it'll be positively buoyant and individual droplets would slowly dissolve; below ~3000m release depth, the plume would sink; intermediate depths, neutral buoyancy spreading of the plume occurs); Liquid CO_2 isolation (CO_2 can be sequestered as a gravity stable deposit on the ocean floor, as a liquid lake, in an ocean floor depression/deep trough, liquid accumulation contained within a geo-membrane, or below ocean-floor sediments). *3.* Chemical sequestration (natural limestone weathering removes ~0.7 Gt-CO_2/year form the atmosphere, transporting ~2.6 Gt/year of dissolved calcium bicarbonate into the ocean, counteracting ocean acidification); Biological sequestration (Ocean iron fertilization – iron is delivered to the ocean as dust carried offshore from arid land masses, to increase primary production of biomass via photosynthesis); Wave-driven ocean upwelling (increasing rate of CO_2 sequestration by using wave-powered pumps to draw cool, nutrient-rich waves to the ocean surface from below the thermocline); Ocean afforestation (cultivation of kelp or seaweed over large areas of shallow, euphotic waters).
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* Can look into using ocean storage methods as Guadalajara is close to the Pacific ocean, and so effort needs to be made to design the DAC facility to transport CO_2 to the coastlines of Mexico (e.g. to Manzanillo, Puerto Vallarta).
Actions: How are you going to follow-up to progress your project work? 1. Do more research into demonstration projects to get a better understanding of the limitations of ocean storage. 2. See if cities near the coastline of West Mexico is suitable for developing infrastructure for transporting CO_2 if we were to go with storing CO_2 in the oceans.

Journal Paper / Book Chapter / Article citation: Romesh P Waisiri. (2019). Industrial and Engineering Chemistry Research Part 58 Chapter 34 - Desorption Process for Capturing CO_2 from air with Supported Amine Sorbent.

https://doi.org/10.1021/acs.iecr.9b03140

Summary: *Provide a brief overview of this text.* This text discusses the effectiveness of steam assisted temperature swing vacuum desorption of CO_2 under different temperatures and pressures. The steam assisted method has a much faster rate of desorption than regular TVSD. All CO_2 was desorbed at pressure levels between 12kPa-56kPa and temperatures between 70 – 100 °C; the highest rate of absorption was at 12kPa at 100 °C.
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. Why is there an increased interest in SSAs (solid supported amines)? 2. What is the most widely studied desorption technology? 3. What is TVSD and why is it applicable for DAC (Direct Air Capture)? How does it compare to TCSD?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1. SSAs are a group of sorbents made up of different amines attached to a solid material (silica, carbon, alumina). They have a high uptake capacity for CO2 and can possibly regenerate under mild conditions. Moreover, their uptake capacities increase in the presence of moisture, which is very applicable as there would be plenty of moisture available in (humid) air.* *2. Temperature Concentrated Swing Desorption (TCSD) is the most widely studied desorption technology and uses SSAs. In this process the sorbent is heated and purged with an inert gas to desorb the CO_2 and while the rate of desorption is quick, the desorbed CO_2 is produced in a dilute form. Higher temperatures and increasing the flow rate of the purge gas speed up the process but only higher desorption temperatures result in a higher concentration of desorbed CO_2. TCSD with CO_2 as the purge gas has also been tested resulting in a high amount of CO_2 being desorbed but at a very slow rate and with some degradation to the SSAs being used to.* *3. Temperature Vacuum Swing Desorption is achieved through applying a mild vacuum to the sorbent as well as simultaneously heating the sorbent. Adding heat removes the requirement for high vacuum levels required in regular Vacuum Swing Desorption and makes this process more viable for Direct Air Capture. Higher temperatures and lower pressures result in the best desorption. TVSD produces slower desorption rates than TCSD, however the purity of CO_2 produced during TVSD is much higher as no inert gas is used.*
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* This paper discusses the use of an amine solvent which is relevant to the project as this is the preferred solvent as it would reduce the complexity of the procedure. It would be practical to consider the use of TVSD or TCSD as the process of desorption in our project, but the disadvantages and advantages of each process must be taken into account. If we want a fast process then TCSD would perhaps be more appropriate but if we want a process resulting in high concentrations of CO_2 being produced then TVSD would be considered more.
Actions: How are you going to follow-up to progress your project work? 1. Conduct further research into TCSD and TVSD and see how they compare to identify which desorption method would be most suitable for the project.

Journal Paper / Book Chapter / Article citation: Zain Ali Saleh Bairq.(2019). Applied Energy- Vol 252, p.11340 - Enhancing CO2 desorption performance in rich MEA solution by addition of SO4 2−/ZrO2/SiO2 bifunctional catalyst.

Summary: *Provide a brief overview of this text.*

The high amount of energy required for regenerating amine solvents is one of the key factors holding back the widespread adoption of an amine-based CO_2 capture system. In the study conducted, five bifunctional heterogenous catalysts were evaluated in their effectiveness of enhancing CO_2 desorption and regenerating the amine solvent.

Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.*

1. How are additives being used to decrease desorption time? Why is it necessary to look for new methods such as the use of catalysts if additives are already being researched?
2. What effects do the catalysts have on the desorption process?
3. What is the most effective catalyst?

Answers (knowledge): *Read the text more carefully and answer your questions.*

1. *Additives such as nanoparticles and metal oxides have been used in the desorption process to reduce the overall time of the process, with titanium oxide nanoparticles saving 42% of the desorption time in one instance. Metal oxide sulphate additives have a high temperature stability allowing for the process to occur at higher temperatures and are also easy to make with low environmental risks too. However, some of the additives are difficult to separate from the regenerated amine solvent and metal oxides tend to deactivate quickly. These additives have not led to the desired large enough deduction to operating costs.*
2. *The catalysts are able to reduce the heat duty (the large energy requirement for amine solvent regeneration and CO_2 desorption), with a largest reduction of 36.48% of the heat duty required for CO_2 desorption compared to without the catalyst. Essentially the catalyst has the potential to reduce the required regeneration temperature from 140 °C to less than 100 °C during the CO2 desorption process. The catalysts also sped up the rate of desorption by 35.1%.*
3. *The most effective catalyst was $SO4^{2-}/ZrO_2/SiO_2$ 15% showing the greatest efficiency compared to any other catalyst.*

Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?*

Could consider using one of these catalysts in the CO2 desorption process that we use, so long as they are affordable and possible to integrate with our designs.

Actions: How are you going to follow-up to progress your project work?

1. Identify if these catalysts can be used in TDSC or TVSC
2.

Journal Paper / Book Chapter / Article citation: Jere Elvfing et al. (2021) Chemical Engineering Journal, Vol 404, 126337- Experimental comparison of regeneration methods for CO_2 concentration form air using amine-based absorbent.
https://doi.org/10.1016/j.cej.2020.126337

Summary: This article discusses the various methods to regenerate amine absorbents during the desorption process. It mentions the different methods for adsorption and desorption and which method of regenerations fits most appropriately with each one.
....

Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.*

1. What are the methods of Desorption and regeneration of amine-based sorbents?
2. When do amine sorbents start to experience degradation?
3. Which method has the lowest Specific Energy Requirement?
4. Is the method of TVSD used in conjunction with a purge gas a viable solution for DAC?
5. What uses can low purity carbon be used for?

Answers (knowledge): *Read the text more carefully and answer your questions.*

1. *TSD is the regular method of regenerating amine-based absorbents, however this results in low concentrated CO_2 being produced as well as the absorbent experiencing some oxidative degradation. To reduce this effect an inert gas can be used as the purge gas instead of air. CO_2 can also be used as the purge gas itself to produce very high concentration of CO_2 , however this could cause urea forming on the adsorbent resulting in the adsorbent deactivating. Saturated steam can be used as a purge gas in a process known as steam stripping which produces high purity CO_2 once the water is condensed from the product gas. However, this process can result in the leaching of amines on the absorbent.*
2. *Amine adsorbents experience a drop in capacity after a certain number of cycles. In this experiment the study reports on there was a drop after 19-23 cycles while in other experiments drops only occurred after 100 cycles, however this is dependent on the regeneration method used and the absorbent used. The graphs show that this is a very steady and gradual drop as the cycles progress.*
3. *Regular Temperature Swing Desorption with isobaric conditions had the lowest SER.*
4. *TVSD used in conjunction with an inert purge gas resulted in over 85% adsorbent regeneration at 60 °C and has a lower specific energy requirement as opposed to regular closed TVSD. This is a suitable option for DAC so long as purge flow rate is kept at a reasonable level. This method allows for better regeneration of the absorbent as it has a better working capacity than closed TVSD and the apparatus is evacuated of air. The low regeneration temperature also allows the use of process waste heat or district heating so this excess heat could be used for greenhouses to be used for the cultivation of algae. This method is most suitable for extraction of low CO_2 concentrations.*
5. *The growth of microalgae only requires a CO_2 concentration of 1-2% .*

...

Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?*
As our stored/transported carbon will be used for the growth of algae, a method that produces a high concentration of CO_2 will not be required. Therefore, regular TVSD along with an inert purge gas would be suitable to produce the required amount of CO_2 and allow for minimum amount of degradation of to the amine absorbent. This will allow for a process that occurs at a low temperature (due to a mild vacuum being applied)

Actions: How are you going to follow-up to progress your project work?

1. I shall share these findings with my team and recommend that we use TVSD alongside an inert purge gas as our method for desorption.

Group: 52 **Reviewer:** Ibrahim Kabir

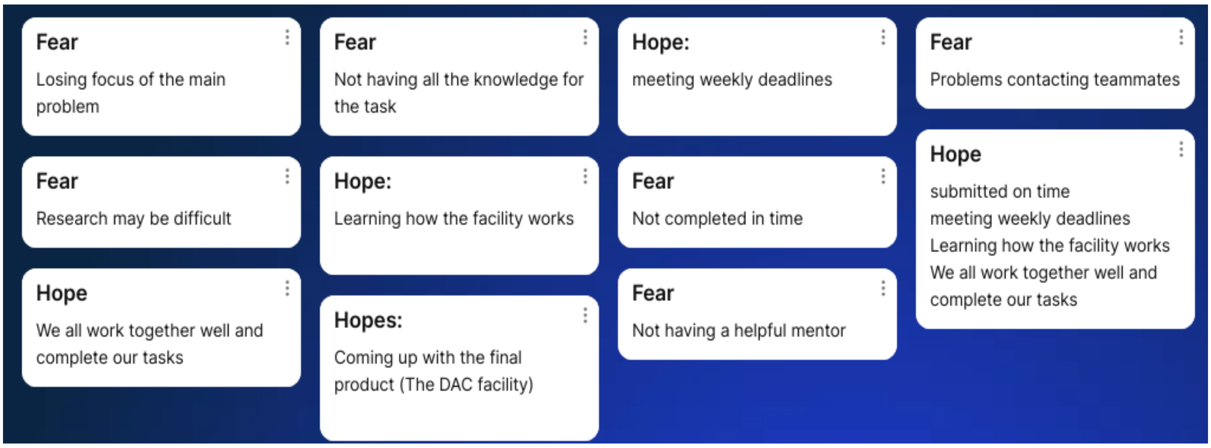
Journal Paper / Book Chapter / Article citation: Bihong LV et al. (2017), Environmental Science and Technology, *49* (17), 10728-10735, 'Mechanisms of CO_2 Capture into Monoethanolamine Solution with Different CO_2 Loading during the Absorption/Desorption Processes'

Summary: *This section explains how MEA solvent is used in the absorption and desorption processes and how it is regenerated.*
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. *How does the desorption mechanism work with MEA?* 2. *How is the MEA solvent regenerated?* 3. *How can the desorption process when using MEA be enhanced?* 4. *What are some of the disadvantages of this solvent?*
Answers (knowledge): *Read the text more carefully and answer your questions.* 1. *Absorption of CO_2 by MEA results in the production of carbamate which is then hydrolised and the formation of HCO_3^- /CO_2^{3-} due to the hydration of CO_2. To desorb the CO_2 some of the HCO_3^- ions will be heated to break down these ions and produce CO_2 while the remainder of these ions will be reacted with carbamaic acid to form carbamate once again which is then heated, decomposing to produce CO_2.* 2. *Likewise, the MEA solvent is regenerated via the heating and decomposition of the carbamate one of the products being MEA.* 3. *The desorption process can be significantly enhanced through the addition of nanoparticles- specifically SiO_2, Al_2O_3 and TiO_2. These nanoparticles reduce the liquid-side-mass transfer resistance significantly increasing rates of absorption and desorption; TiO_2 particles saved 42% of desorption time.* 4. *Regeneration of the MEA solvent requires a very large amount of energy.*
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* This is a liquid solvent which means it meets certain requirements of the project. The desorption methodology could be directly integrated into the research section of the report should MEA solvent be used in our final design. We could also consider how to implement the nanoparticles into our system to make it more efficient. Further research would need to conduct on the size of desorption towers so that they could actually be designed in CAD software.
Actions: How are you going to follow-up to progress your project work? 1. Compare this solvent technique to other solvent techniques and establish which is more novel and effective. 2. Discuss with the group member researching absorption so see if his method is complementary to this desorption method.

Journal Paper / Book Chapter / Article citation: Stephen A Rackley (2017), Carbon Capture and Storage, P. 115-149, 'Absorption Capture Systems'

Summary: This journal chapter provides information of absorption and desorption of CO2, using a sodium hydroxide solvent. It explains how CO_2 is separated from the solvent used to capture it and how the solvent is regenerated.
Questions (aims): *Skim read the text and diagrams. Identify questions could help you progress your project. You can revise these while you try to answer them.* 1. How is the carbon dioxide separated? 2. How is sodium hydroxide regenerated? 3. How can the process be made more efficient?
Answers (knowledge): *Read the text more carefully and answer your questions.* *1. Sodium carbonate is produced once CO_2 comes into contact with the solvent and cycled out of the absorption tower into the causticizer where it becomes calcium carbonate. This calcium carbonate is the sent to a calciner where it is heated at around 900 °C to produce water vapour (steam), lime (calcium oxide) and CO_2. This CO_2 (typically being of 35%-50% purity) is then siphoned off to be compressed for storage and other uses.* *2. NaOH is regenerated via the causticization process. Firstly, the lime produced in the calciner is cycled to the slaker where it is hydrated to produce calcium hydroxide (slaked lime). This slaked lime is then passed into the causticizer where it is reacted with sodium carbonate to produce sodium hydroxide.* *3. The energy consumption of the process could be made slightly more efficient by recovering heat from steam produced in the calciner. Moreover, as the slaking reaction is exothermic low level heat recovery could be applied to this process too.*
Impact: *Consider which elements of the text can be directly incorporated into your project. Are you still missing something?* Much of the answers could be used in the research section of the report as they describe the desorption process of the CO_2 when a sodium hydroxide is used. When it comes to designing the facility a calciner, causticizer and slaker would have to be included. The purity of the carbon produced may limit what it could be used for.
Actions: How are you going to follow-up to progress your project work? 1. I shall share this information with my group especially the group member working on absorption so we can establish what machinery we shall need for the facility. 2. Research into how to improve this process.

APPENDIX D: Lab exercises



Week 1 (03/02/2022): *Hopes and fears exercise*

IDP2 Sustainability Part 2 LCA worksheet 17/2/2022

Exercise A: Life-Cycle Thinking

1:

Product	Energy intensive phase
Coffee Maker	Product Manufacture
Bicycle	Product Manufacture
Motorbike	Product Use
LPG fired patio heater	Product Use

2:

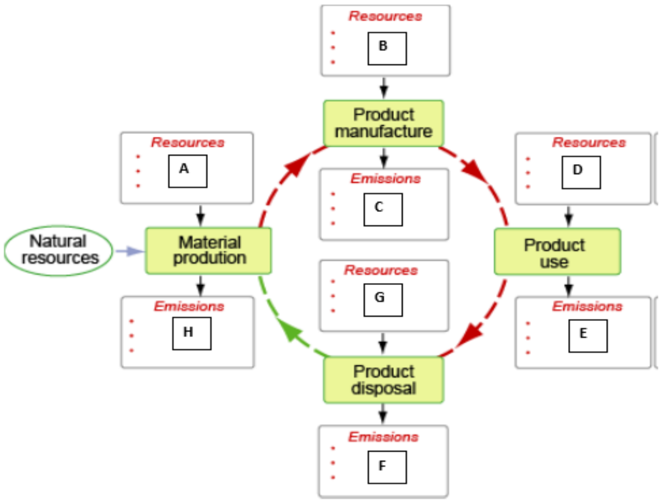
Product	Functional unit
Washing machines	E.g., Energy (kW.hr or MJ) or litres of water *per kg of clothes washed*
Refrigerators	Energy per Kelvin temperature decrease
Lighting	Energy per light hour
Public transport	Energy per person transported/mile travelled

3:

	Material	Manufacture	Transport	Use	Disposal
Materials resources (high use =0, none =4)	2	2	1	1	1
Energy Use (high use =0, none =4)	2	3	1	1	1
Global Warming (much CO_2 = 0, no CO_2 = 4)	1	2	3	1	1
Human Health (Toxic emissions or waste?)	1	0	1	0	1
Column Totals	6	7	6	3	4

Total across columns= 26

IDP2 Sustainability Part 2 LCA worksheet 17/2/2022



A

- Energy
- Concrete
- Sandstone

B

- Energy

C

- Carbon Dioxide

D

- Energy required to run the facility.

E

- Reduces amount of carbon dioxide in the atmosphere.

F

- Landfill
- Combustion

G

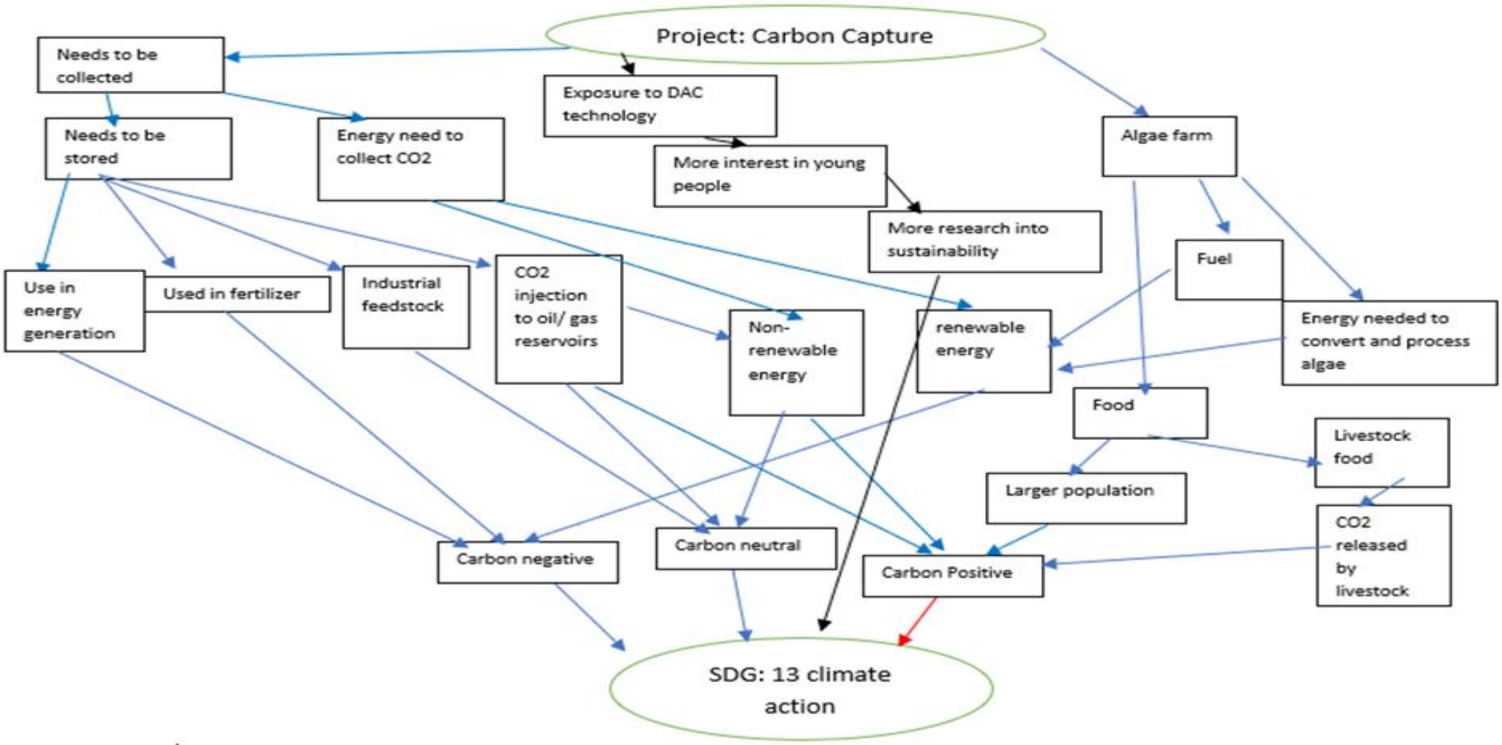
- Energy

H

- Carbon dioxide
- Solid waste
- Liquid waste

Consider using the above diagram and filling in the blanks to produce an LCA for your project.

Week 3 (17/02/2022): *Sustainability LCA worksheet*



Week 3 (17/02/2022): *Sustainable Development Goals Worksheet*

IDP2 Professional Skills 6 - Business Enterprise Worksheet

Exercise A:

Answers to questions:

1	d) Technological
2	c) Registered Company
3	a) Functional
4	a) Increase Trend
5	a) Bank Loans
6	a) Less than 1
7	b) 2
8	a) 2.3
9	a) Yes

Exercise B: Business Organisation / Commercial

1) Our design group operates as a consultancy. We don't produce any products and have no fixed assets. Our only asset is the knowledge we have as a group.
2) Research focussed, risk mitigation, carbon capture neutrality, and remote working.
3) Knowledge/Intellectual property and design.

Exercise C: Marketing analysis

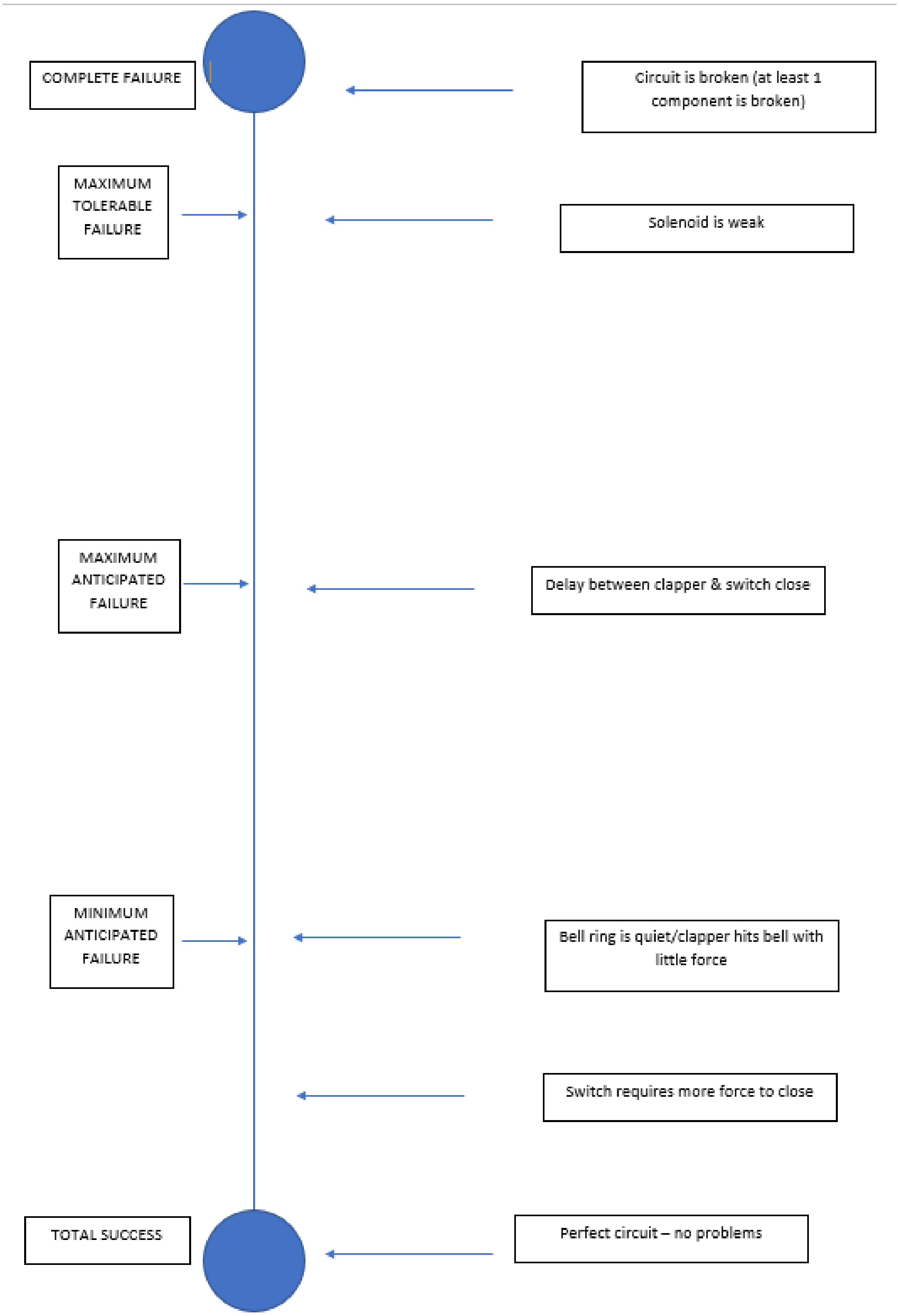
We are producing a product with multiple uses across different industries. Our facility is designed to be based in Guadalajara and within the immediate area we are helping reduce food shortages by providing a food supply. Promote the environmental aspect of our facility as it is carbon negative as it captures carbon from the ambient air.

Exercise D: PEST

Political	Economical	Sociological	Technological
Governments around the world have committed to reducing carbon emissions and are aiming to reach carbon neutrality to prevent the crisis of global warming	The captured carbon could be sold to businesses/industries that require it. The demand for carbon is expected to increase by 1.7% on a yearly basis.	Lack of education on reducing carbon emissions within Guadalajara. The DAC facility could be used as a teaching facility for the general community, as well as those who come to visit. If the facility is successful, it could also encourage the building of more facilities.	There is a lack of effective carbon capture technology. Current methods have a very high specific energy requirement, or the sorbents used tend to degrade after multiple cycles. More effective and less energy intensive methods need to be developed.
	Guadalajara is the third largest city in Mexico and so would always welcome the creation of more jobs. These jobs being: DAC facility workers, algae farm workers and truck drivers.	Generational job progression: creating jobs now allows people to afford better lifestyles and education allowing their future generations to further improve their lives.	Currently the captured carbon is mainly being stored underground. Methods to use this carbon in a more useful manner need to be developed.

Week 4 (24/02/2022): *Business Enterprise Worksheet*

1) Failure space-success space



2) Mechanisms and failure mechanisms.

Mechanism	(a)	(b)	©
Wire	Open circuit	Short circuit	Short circuit
switch	Bad connection	Switch short circuits	Switch bounce/ gets stuck down
solenoid	High resistance/open circuit	Induced field causes clapper to move on its own	Induced current causes clapper to still move
battery	Dead battery	Bypasses switch due to crossed wires	Bypasses switch due to crossed wires

3) FMEA

Mechanism	**Failure Mechanism**	**Failure Mode**	**Effect**
Wire	Shock	Loose wire/lost connection.	(a) Open circuit
Wire	Ground fault.	Loose wire	(a) short circuit
Switch	Button doesn't close switch	Loose button	Open circuit-Replace button
Switch	Button doesn't return to default	Compressed button	Short circuit-Decompress button
Solenoid	Solenoid doesn't move clapper	High resistance	Bell doesn't ring-Replace solenoid
Solenoid	Solenoid continues to move clapper	Induced current/field	Short circuit- bell continues to ring-Adjust solenoid sensitivity/replace solenoid
Battery	No voltage	Dead battery	Bell doesn't ring- replace/charge battery

4) HAZOP

Guide word	Consequence	Causes?
No	No power supplied to the solenoid.	Battery failure or dead battery.
More	Bell continues to ring after button released.	Faulty push button resulting in a short circuit.
Less	Bell does not ring when pressed.	Faulty push button results in an open circuit.

As Well As/Part of	Dull sounding bell or clear sounding bell	Type of bell
Reverse	Switch input does the opposite as intended	Push to break switch- when pressed switch breaks circuit
Other than	Button not pressed but doorbell rings.	Short circuit.
Early/Late	Output is delayed	Faulty wire
Before/After	Bell continues to ring after switch release	Faulty switch remaining in close position after releasing force

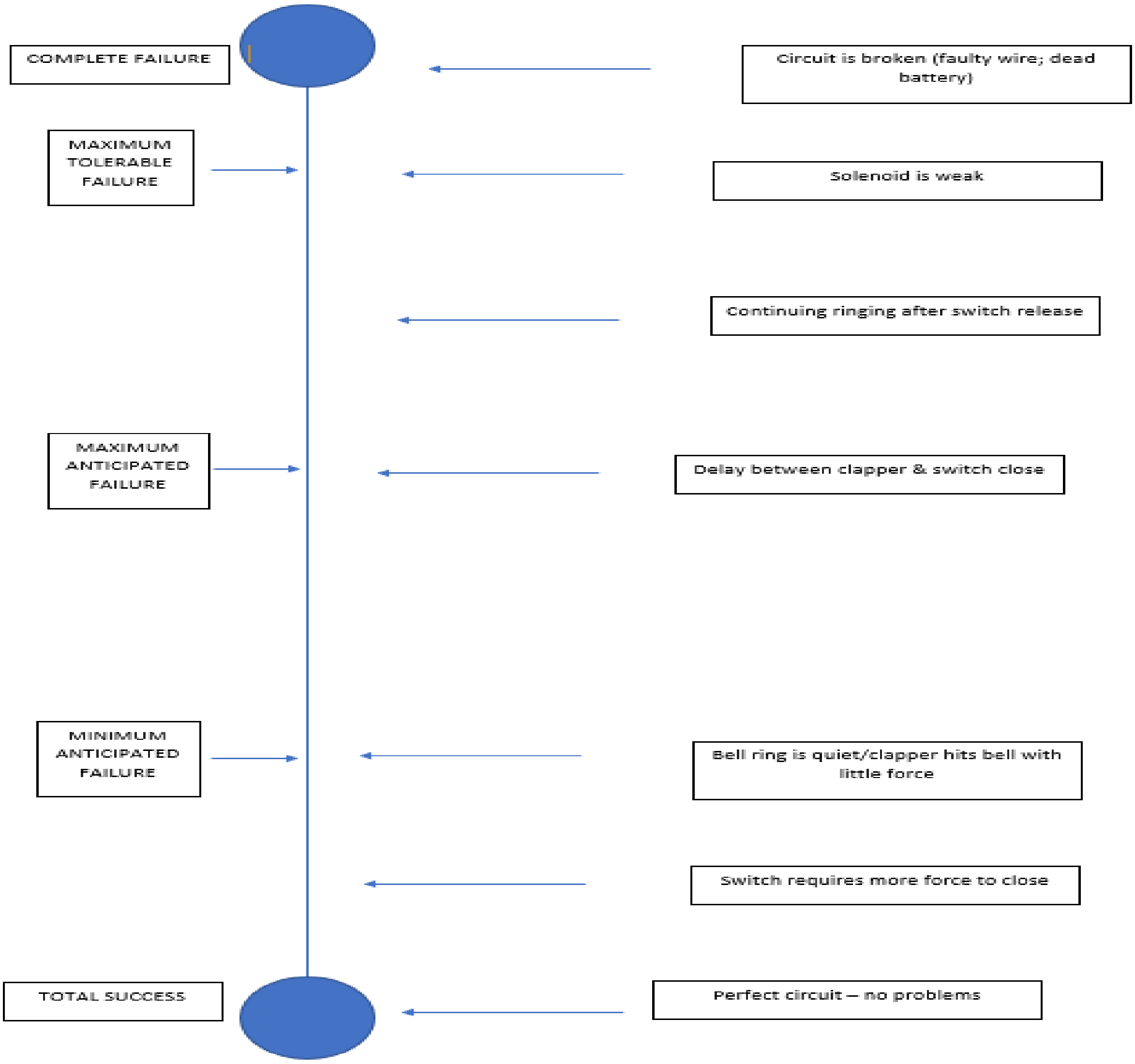
4a) What value does HAZOP have over the information in FMEA?

Hazard and Operability Technique is an analytical technique used to identify potential accidents. It has since progressed in having applications for safety critical electronic and computer systems, since its initial launch in the chemical industry. Although it is old it is still widely used due to its simplicity in 4 basic steps. The Failure Mode, Effects and Criticality Analysis is to identify failures in the products or processes to limit and mitigate any potential risks. The information in FMEA focuses on both safety as well as performance, quality, and reliability, whereas the HAZOP is focused solely on safety hazards.

4b) How is HAZOP related to FMEA i.e., what information do they share and how can they be used together?

There are slight procedural differences however as the scope of a HAZOP is safety hazards, a design FMEA will need to be carried out in addition to hazard analysis to improve the product design. Furthermore, a process FMEA will also need to be carried out to improve the manufacturing process. The impact of the risk on a product will be reduced by implementing minimisation strategies such as HAZOP then if the risks were to escalate a contingency plan would be put into operation in the form of FMEA/FMECA.

4c) failure-space success space model to include information from Hazop:



5) Considering your challenge

a, b, c) RAG risk matrix

<u>Number</u>	<u>Risk</u>
1	CO_2 leakage via compromised impermeable barrier or caprock
2	Seismic activity from geological trapping
3	Bad weather – poor sunlight for algae growth
4	Pipelines for CO_2 transport can be damaged by environment
5	Knocking over algae containers
6	Someone falling into the fans
7	Solvent getting in contact with skin and eyes

8	Algae settling in photobioreactors
9	Flooding damaging facility
10	Algae contamination
11	

Severity/ Likelihood	*Low*	*Medium*	*High*
Low	**10**	**7**	**6**
Medium	**3, 5**	**3, 8**	**1, 2, 4,9**
High	**-**	**-**	**-**

d) use of FS-SS, FMEA, FTA and Hazop

The FS-SS can be applied to the fan/air intake system. The complete failure would be where the fan doesn't move, and no air is taken into the facility. Maximum tolerable failure would be where the fan spins but at a low speed.

The FTA model can be applied to the possibility of the structure collapsing as flooding is a possibility and the fans could come loose, damaging the structure on the way down. Another example is the algae farm failing as it doesn't get enough sunlight, CO2 and nutrients. This would lead to a large waste of algae and the possibility of harmful algae forming that release toxic chemicals

The HAZOP model can be applied for the CO2 capture system regarding the intake machinery. Examples could be if the intake fans are not working at the maximum safe capacities, then less CO2 is being taken out of the atmosphere. Another example would be if there were no power given to the intake fans, then no CO2 would be taken and stored, making the DAC facility useless for the time being.

The FMEA model can consider the intake fans as the mechanism, with the failure mechanism being the fan not moving, this could be due to not enough power reaching the motors. This can be resolved by increasing the power to the motors or using a better speed controller.

e) Applicability of reliability engineering techniques to your challenge:

Accelerated Life Testing: *Pipeline can be subjected to stresses, temperatures, pressure and corrosion to simulate the environment the pipeline will be situated in.*	Antifragile: The DAC facility would need to have a strong structure to withstand all weather conditions. The fans should also be adaptable and resistive to strong winds that could cause the fans to spin to fast and break the axel it is on

Bulkhead: Bulkheads can be used to isolate areas of the facility to prevent further damage in the event of a leak.	Change Control: The facility will have to be adaptable to the changing world as it will be produced in the future and is meant to last for
Cold Standby: Facility has a backup power source in the event of a blackout to allow the facility to continue working.	Defensive Design: When designing DAC facility, include flood barriers in case of floods, and earthquake defences such as shock absorbers or flexible foundations in case of earthquakes which are quite common on the west coast of Guadalajara. Also design facility away from volcanoes, especially Colima (last eruption in 2017).
Derating: Fans used intake less air than usual if transport fails to either the recycling facility or storage site.	Design Debt: When designing a building the DAC facility, the materials selected could be weak and degrade quickly. This would mean that the structure would have to be replaced often costing lots of money and reducing the time that the facility is in operation
Design Life: Plant has a fit for purpose design life of 10 years.	Design Thinking: Look into architecture in Guadalajara to get inspiration and make the facility stand out in a positive way whilst still maintaining the visual theme (colour palette, common materials) of the city.
Durability: Ideally, machinery included in the DAC facility should last as long as possible till the end of the facility's life cycle, to avoid consistent machinery replacements, which will add up in operation costs. Materials used should be of high quality but economically viable to obtain.	Edge Case Earthquakes can occur due to Mexico lying within a subduction zone, though rare, earthquake mitigation measures need to be applied to prevent major damage (Guadalajara is located quite far away from the western coast, so earthquakes should only have small effects on the facility).
Entropy: The facility will have to be maintained to ensure that the systems that run on the best software and that the building is repaired if damaged. It will also have to rely on mainly renewable energy sources as Fossil fuels will eventually run out and also pump more CO2 into the atmosphere	Error Tolerance: Machinery for operation of the facility can alert users via a computer screen if parameters are or need to be adjusted outside their desired ranges. The computer programs could outright prevent parameter adjustments outside their desired ranges.
Fail Well: Letting algae build up to maximum capacity in photobioreactors to simulate scenarios where computers aren't automatically harvesting excess algae to keep optimum microalgal concentration levels. Can be easily tested as it doesn't damage the photobioreactor, and can be cleaned/harvested manually to solve the problem.	Fail-safe: As Mexico is prone to many earthquakes and hurricanes, it's best to have a failsafe where it has seismic or weather sensors to shut down certain machinery like intake fans, &/or have the facility go into lockdown to protect the facility to avoid massive maintenance costs.
Fault Tolerance: Facility can continue to extract carbon dioxide from the air even when some fans are inoperable.	Graceful Degradation: If using renewable energy such as solar or wind to power the plant, which these resources are not constant, the facility can adjust itself to use less power when this happens, instead of just shutting down and being completely useless.
Human Error: Make the DAC facility as automated as possible, where most work would just be operation &/or	Human Factors: DAC facility should be aesthetic for non-users, which would increase public opinion on artificial CO2 capture, which may

maintenance. Have machinery that's easy to operate (not complex, which would require more training time, and complex generally opens the user to more errors)	lead to more policies that would aid in tackling climate change. Facility must be as automated as possible, to reduce amount of manual labour work.
Latent Human Error: The facility should have a sensor by the fans so when they are off, if someone is doing maintenance, it cannot be turned out until it is clear.	Maintainability The maintenance of the facility will be relatively low as it is designed for a 10-year life cycle. The only regular maintenance that would be required is on the pipeline to predict fatigue and failure before it occurs. This will prevent potentially serious threats caused by the release of carbon dioxide.
Mistake Proofing: Systems in place so that human error cannot occur. For example, a system which would prevent the facility from running if drops in pressure of carbon dioxide is detected in the pipeline.	No Fault Found: If a fault was found within the facility, there should be sensors that can detect and confer with reported issue so it can be solved.
Pokayoke: System designed so that pipeline cannot be replaced or exchanged whilst carbon dioxide is still present in the pipeline.	Resilience: The facility will have flood defences to endure any flooding that occurs, it will also run off mainly renewable energy and the structure will take into consideration that earthquakes can occur so will be able to handle them
Root Cause: In our DAC facility the root cause can occur from multiple sources: design failure, human error, unmanaged risk and quality control.	Safety By Design: Emergency cut-off system in the rare event of an earthquake or other natural disaster to stop the processing of carbon dioxide to prevent leaks.
Self-Healing: NA	Service Life The DAC facility is designed to have a service life of 10 years. After which the infrastructure can be abandoned following safety procedures.
Systems Thinking: In the context of larger systems the DAC facility we are designing will reduce the amount of carbon dioxide in the atmosphere to reduce the effect of the enhanced greenhouse effect.	Testbed: Can be used on the pipeline to ensure the material and design is capable of withstanding use for at least 10 years.
Wear And Tear: The decline in quality of physical items over time can be minimised in our design by designing components of durable material. Smaller components such as fan blades can be replaced easily; whereas pipelines will be designed to last as these will be expensive and take large amounts of time to replace.	

Week 4 (24/02/2022): *Risk & reliability worksheet*

APPENDIX E: Equation Sheet

Transport

Equations

$ID = \sqrt{\frac{4Q}{\pi \bar{U}}}$ (1)

$t = \frac{P_{max} ID}{2(SFE - P_{max})}$ (2)

$OD = ID + 2t$ (3)

$P = \frac{q \times h \times p}{367}$ (4)

Reuse

Conversion from m^3 to kg of CO_2: 1 m^3=1.84 kg (5)

Calculations

To calculate the inner diameter (ID) of the pipe equation 1 [7] was used. Volumetric flow rate (Q) of 0.086 m^3/s and fluid velocity ($\bar{U}$) of 2 m/s to give an inner diameter of 0.23418 m.

The thickness of the pipeline was given by equation 2 [7]. Using a maximum pressure (P_{max}) of 17 MPa, inner diameter (ID) of 0.23418 m and longitudinal joint factor of 1. The design factor (F) – 0.72 was given by the CFR regulation of carbon dioxide pipelines and the specified minimum yield stress for the pipe (S) is 483 MPa to the American Petroleum Institute specification. This gives a pipe thickness of 0.00602 m.

The outer diameter of the pipe was given by equation 3 [7] using the values of thickness and inner diameter calculated to give an outer diameter of 0.24621 m.

To calculate the power used by the pumps in the pipeline equation 4 [8] was used. A flow rate (q) of 310.11 m^3/h was used with a density (ρ) of 0.0018393 kg/dm^3. The head (h) was 1 m. This gives the total power required by one pump as 0.00155 kW. This is equivalent to 48.88 MJ per year by each pump.

To calculate the amount of CO_2 the algae farm will use, the volume of water in each photobioreactor was predicted to be 2000 L. multiplying by the number of photobioreactors, the total volume is 80000 L. Converting this to m^3 gives 80 m^3. Assuming that each tank is full of algae, converting this to kgs of CO_2 using equation 5 and that the CO_2 absorption volume is 50% gives us 73.44 kg of CO_2 per day. For the year, this gives us around 27 tonnes of algae a year.