Department of Mechanical and Aerospace Engineering

Microalgae for CO_2 Sequestration from Fossil Fuel Power Plants: The Global Potential

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ABSTRACT

Biomass naturally sequestrates carbon dioxide. Microalgae is a form of biomass that grows by photosynthesis and its growth can accelerate when supplied with carbon dioxide. Microalgae is an easily accessible and cheap product, with numerous positive post growth uses including bioenergy. Microalgae's versatility means it may have a high potential to be an integral part of the low carbon future that the world is aiming for but as the world is aiming for a low carbon future, there will be a transition period in which carbon emissions will constantly be high. This transition period needs to be addressed and carbon sequestration methods are one such way that can address this and could play a very important role in transitioning so need to be analysed.

This thesis will evaluate the global potential of microalgae for sequestrating carbon dioxide (CO_2) directly from fossil fuel power plants (FFPPs). The analysis will profile the carbon emissions associated with all coal, oil and gas power plants globally. Different microalgae carbon sequestration technologies are considered culminating in microalgae raceway ponds (RWPs) being the technology chosen for the analysis. The global potential is analysed prioritising CO_2 sequestrated and RWP size required. An economic analysis is completed with these results and evaluated against other carbon sequestration technologies.

The analysis showed that coal power plants (27% of all FFPPs) produces 70% of carbon emissions from all FFPPs – 9.97GtCO_2/Year. All FFPPs produce 43.54% of energy related carbon emissions. Microalgae RWPs can sequestrate up to 80% of global carbon emissions under the assumptions made. The power plants were categorised by their installed capacities for the analysis. RWPs up to 227,131m^2, but as small as 5,884m^2, would be required to keep the 80% CO_2 sequestration across the categories. The microalgae would need to be harvested as often as once a week but can be as often as once every 5 years at. The economics associated with the RWP sizes calculated in the carbon sequestration analysis find that microalgae RWPs, where harvesting is required once every two weeks on average, could give a price of £1.81per Tonne of CO_2 sequestrated.

Using microalgae, once harvested, is not analysed in detail within this thesis. The focus of the microalgae is on sequestrating carbon; the potential of this and costs associated. The value of microalgae however goes beyond carbon sequestration and should not be forgotten.

ACKNOWLEDGMENTS

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To my mother for providing a place of residence and always listening to what I had to say about my thesis, even though she didn't 'understand a word of it but it sounds and looks good'. Thank you for going through this and ensuring it made as much sense as possible. And to the rest of my family, thanks for regularly being available to meet up and break up the intensity of the thesis, productively.

Thank you to my cats. It is true, stroking cats provide stress release and I do believe on a subconscious level this kept me relaxed and concentrated throughout this project.

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NOMENCLATURE

CO_2 – Carbon Dioxide

FFPP – Fossil Fuel Power Plant

GEO – Global Energy Observatory

GHG – Greenhouse Gas

Gt – Gigatonnes

MW - Megawatts

PBR – Photobioreactor

RWP – Raceway Pond

S.I – Standard Imperial

WRI – World Resources Institute

1 INTRODUCTION

This chapter introduces the project, by describing the problem at hand and how this project will address it. A clear aim with objectives is then formed and the logical structure to reach the project aim is outlined.

1.1 PROBLEM DEFINITION

As the world is trying to move towards a low carbon future, for the sake of future generations of humanity, global greenhouse gas (GHG) emissions are actually on the increase year upon year and expected to be like this until 2030 (Levin, 2017). 92% of all GHG emissions have carbon in them and 83% of these, containing carbon, are carbon dioxide (EPA, 2017). Due to this majority, when referring to GHG emissions many shorten it to Carbon Dioxide (CO_2) emissions or just carbon emissions for short and this will reflect within this thesis.

Serious concerns for global warming and the rate it is happening are evident in the 2030 estimates stated above. Many countries are attempting to reduce their carbon emissions as part of the Paris Climate Agreement (UNFCCC, 2018) but if the global emissions are still increasing it is having zero to little effect in the present moment. With the developing countries increasing their energy demand and the population increasing all over the world, meaning more energy demand that needs to be supplied, carbon emissions will increase as renewable technologies cannot cover this demand. This reinforces the original point of the estimations to 2030.

The overall transition for the world lowering its carbon emissions by moving to renewable and low carbon technologies, of better efficiencies than current technologies, mean a period of sustained high carbon emissions that could have an extremely negative effect for global warming. A requirement to assist this transition period is clear and one way of doing so is by stopping emissions reaching the atmosphere through carbon sequestration methods. If these types of technologies can be utilised quickly they can help to reduce the sustained high emissions.

A major cause of global carbon emissions are fossil fuel power plants (FFPPs). 25% of total carbon emissions are from supplying heat and electricity, the majority of which is from power plants (EPA, 2017). Sequestrating as much of this as possible would make a serious positive contribution to the reduction of global emissions.

The Industrial Revolution signalled the start of the serious increases in carbon emissions (EPA, 2016). Natural carbon sequestration happens every day and one such natural living product of earth that does this is biomass. The Industrial Revolution led to millions of biomass, in the form of trees, being cut, that were naturally sequestrating carbon. This further increased the carbon in the atmosphere. Knowing that biomass can sequestrate CO_2 has led to tree planning and therefore more trees being planted across the world in a small but helpful gesture considering the current predicament (Bloch, 2017).

Microalgae is becoming a more recognised form of biomass due to the hundreds of thousands of species that exist (Guiry, 2012). Not only this but the varied properties microalgae has can have a seriously positive influence in industries such as medication, cosmetics, food consumption and can be used for bioenergy (Anyanwu, 2018). Most of these properties will not be overly explored in the project because the focus is on carbon sequestration, but it may be worth investigating a global strategy where which microalgae is used for carbon sequestration, its positive use once harvested and where it is grown can all be considered. Microalgae is cultivated naturally by photosynthesis and can be grown on and offshore. Its growth is accelerated by CO_2 (Patidar, 2017) which means that using microalgae for importantly sequestrating carbon has an extra benefit to it.

Microalgae will be utilised as a technology for carbon sequestration from FFPPs with evaluation on how much of a positive effect it could have on a global scale.

Figure 1 summarises the problem definition.

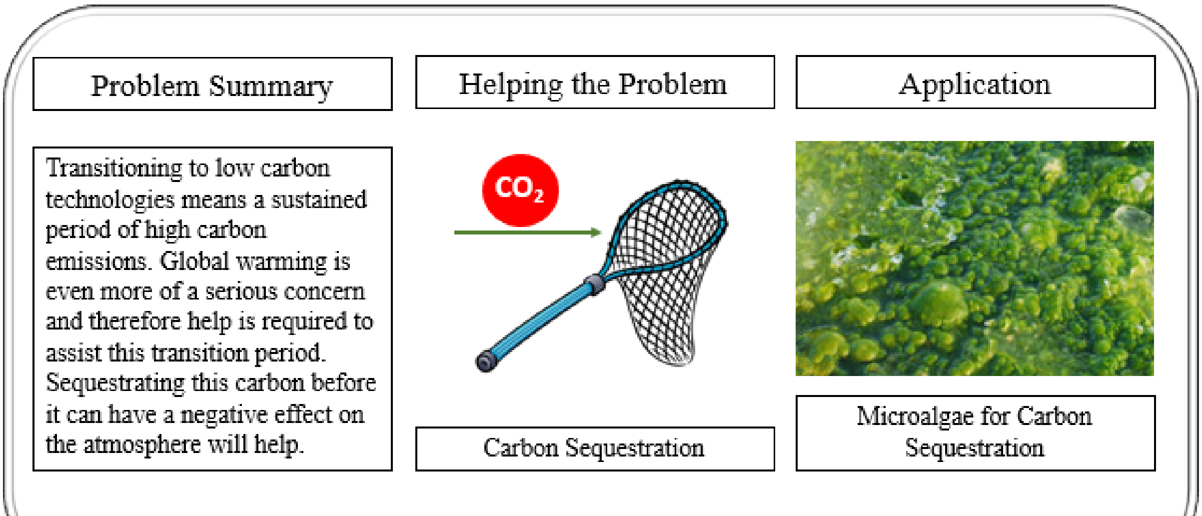

Figure 1 – Problem Definition

1.2 PROJECT AIM

The aim of this project is to explore microalgae as a carbon sequestration technology and the effect it could have if utilised on a global scale.

The objectives of the project are as follows:

- Profile all FFPPs in the world and analyse the CO_2 emissions associated with them.
- Choose a microalgae carbon sequestration technology for analysis and evaluate its potential if implemented at all FFPPs in the world.
- Complete an economic analysis of the findings and compare the chosen microalgae technology with other carbon sequestration technologies.

1.3 STRUCTURE OF DISSERTATION

Having described the problem area and necessity for research in this area, a clear project aim has been developed. From this, the logical steps to the desired outcome; fulfilling the project aim can be made.

The first section that will be undertaken is the Literature Review which is broken into three sub-chapters:

- Carbon Emissions
- Carbon Sequestration
- Economics

These three sub-chapters are integral to each project objective. The 'Carbon Emissions' sub-chapter will review literature to help profile all FFPPs around the world and the carbon emissions associated. Cross referencing is important in this area. Coal, oil and gas power plants respectively will be split due to their varied properties particularly with regards to carbon emissions. A calculation that can be used for each of the three types of FFPPs will then be found which will be used in the analysis to calculate the carbon emissions associated with each.

The next sub-chapter is for researching the technologies associated with carbon sequestration. Microalgae for carbon sequestration is the focus within this section. The properties that influence CO_2 sequestration need to be reviewed and simplified for extrapolation to all power plants worldwide. The different microalgae technologies will be separately reviewed ultimately helping to select which technology would be 'best' for worldwide use for this project. Lastly, other technologies will be reviewed for comparison and the economics associated with all the technologies is reviewed for the final economic analysis.

After the Literature Review, a chapter will outline the Methods that will be used to complete the Analysis and Results chapter. The Methods will describe the logical steps to the results. The Analysis and Results chapter will then complete the logical steps described in the Methods chapter, accompanied by values and discussion. Having then fulfilled the three main objectives within the project aim, the project will be concluded with the Conclusion, References and Appendices.

2 LITERATURE REVIEW

This chapter captures varied but relevant literature to ensure the best chance of success for the project aim. Each sub-section is ordered logically with data to contribute directly to the Analysis and Results chapter.

2.1 CARBON EMISSIONS

As stated in the introduction, from all carbon-based emissions in the world, 83% are carbon dioxide (EPA, 2017) and this majority means when referring to CO_2 using the word ‘carbon’ is often referred to and will be in many instances throughout this project. This project focusses on FFPPs and sequestrating the carbon that they produce.

(IEA, 2017) stated that worldwide CO_2 emissions produced, from energy related sector, was 32.5gigatonnes (Gt). This was a 1.4% increase in carbon emissions from 2016. The energy related sector consists of more than just the production of energy through FFPPs but the mining and transportation etc involved with it. This projects focus is on FFPPs and this links to the ‘electricity and heat’ sector. The energy related sector includes the electricity and heat sector. Knowing that 32.5Gt of CO_2 emissions were produced within the energy related sector gives reference for calculations made within the analysis.

Globally, electricity and heat production create 25% of all carbon emissions and this is the highest percentage of all the carbon emissions production (EPA, 2017). Figure 2 shows the sources percentage split for all worldwide carbon emissions. This includes more than just the energy related sector.

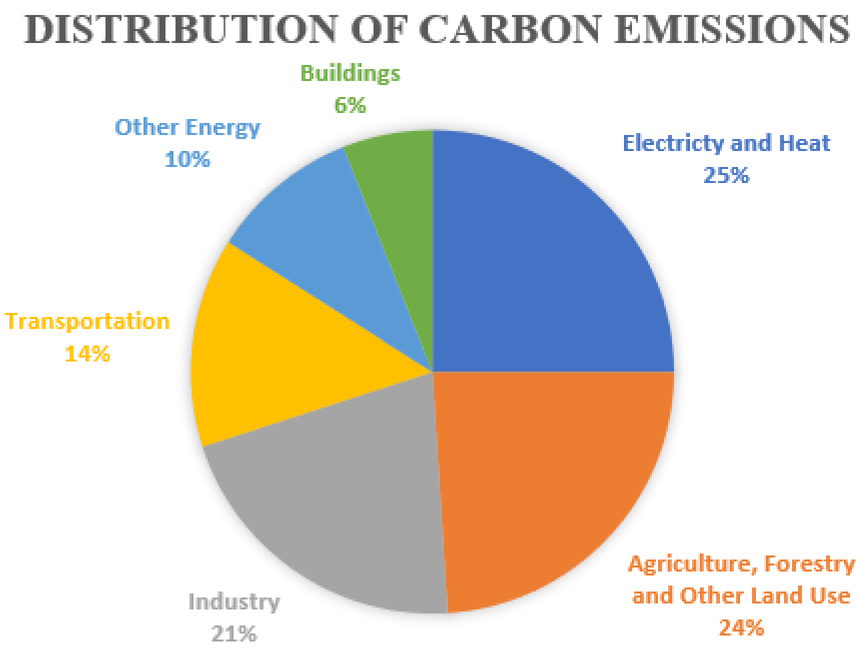

Figure 2 – Distribution of Carbon Emissions

This mainly comes from burning fossil fuels, except for wood, but not all of the 25% comes from burning fossil fuels in power plants. and an example of where some of the 25% is not met by power plants is individuals that use heating oils to heat their own homes. Sometimes this is individual preference, or it's required because they are off grid. This is the same situation where wood would be used.

(Quaschning, 2015) shows statistics for the amount of CO_2 produced by different fuels in 'kilograms of CO_2 per kilowatt hours ($kgCO_2/kWh$) and each source is under 0.4 $kgCO_2/kWh$ with Kerosene (commonly used in off grid heating) at 0.26 $kgCO_2/kWh$. According to (OVO, 2018), a typical house uses 5,000-30,000kWh for heating a year so if we said that the types of houses off grid are leakier and said they used 50000kWh in a year for heating, using kerosene as the fuel, that would create:

$$50{,}000 \times 0.26 = 13{,}000\text{kg of } CO_2 \textit{ per year}$$

When considering gigatonnes of CO_2 this is a negligible number, even when multiplying up by 100,000 it is still negligible, at $1.3\text{x}10^{-4}$tonnes of CO_2, so the figure of 25% will be used when considering the percentage of carbon emissions created by FFPPs for electricity production.

2.1.1 COAL POWER PLANTS

Coal power plants produce the most carbon emissions of all the power plants and are of the most importance to this project. The world of coal power plants fluctuates so much more than either gas or oil. Particularly close attention needs to be paid to this section to ensure the Analysis and Results chapter is as valid as possible.

There is an accessible website dedicated to listing all worldwide power plants. The ‘Global Energy Observatory’ (GEO), (GEO, 2018) has a separate list for coal, oil and gas power plants respectively which is very helpful as each type of fuel creates different carbon emissions per weight burned.

The installed capacity is sometimes known as ‘rated capacity’ or in the case of the GEO website ‘design capacity’. This is the maximum possible output from the power plant, where it would have to be continuously in use at its rated capacity. A capacity factor gives the realistic output that the plant would achieve factoring in various factors like being turned off for cleaning or demand being low at a certain time (so output would be low) and various other factors. Installed capacities are key to this project due to the categorisation that will be made for the carbon sequestration aspect.

(GEO, 2018) stated the databases were last updated on the 20th May 2018 and so were assumed to be up to date at first, but when cross referencing with (EndCoal, 2018), that has a tracker of all coal powered plants in the world, and was last updated in July 2018, the databases clashed. EndCoal’s reference states there are 2440 operating coal plants whereas GEOs reference states there are 1448 operating coal plants. This is a significant difference and needs to be investigated.

EndCoal’s global coal power plant tracker was investigated first and Figure 3 shows an image, taken from the website, that shows the tracker in use.

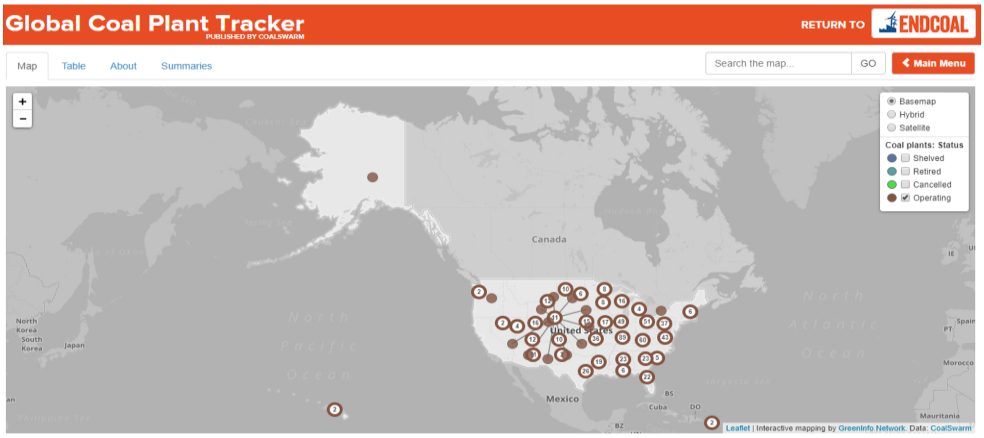

Figure 3 – Global Coal Power Plant Tracker

The tracker can be set to show all coal power plants within a certain country or group of countries. Within this it will then show different numbers on the map which accounts for how many coal power plants are in that region. Figure 4 shows a close-up view of this. I have set it to show all coal power plants in the United States.

Figure 4 – U.S Coal Power Plant Tracker

The darkened circles are single coal plants within that region. If you select one of these it shows the ‘tracker info’ including the name and installed capacity of the power plant. Unfortunately, to assemble a table like that in Appendix A it would be a massively laborious task that would take huge amount of time. The categories of different installed capacities are so important for the carbon sequestration and economics and GEO provides but further cross reference to enhance this or replace this. EndCoal also does not have the lists for gas and oil power plants unlike GEO which does.

Further research found an article that also has a graphic with all the coal power plants in the world (Infographics, 2017) very similar to the EndCoal graphic. Within this article it states that China and India have had an 'explosive growth' of coal fired power plants in recent years. Both Infographics and EndCoal have China and India at the forefront of their data. This will be because these two countries have over 50% of the installed capacity. According to Infographics, China has 935,472MW of installed capacity and India has 214,910MW of installed capacity for coal power plants. The total installed capacity across the world for this is stated as 1,996,426MW so:

$$\frac{935{,}427 + 214{,}910}{1{,}996{,}426} \times 100 = 57.6\%$$

57.6% of the total is from China and India alone. EndCoal had minimally different values but gave a total of 58.7% close enough to confirm the Infographics data.

The issue with the data from GEO could lie with the Chinese and Indian power plant data due to the 'explosive growth' and is just outdated in these aspects so this was investigated. According to EndCoal there are 1003 and 292 coal powered plants in China and India respectively. GEO has 83 and 149 coal powered plants in China and India respectively. The difference in the Chinese and Indian plants is 1063 plants which would make up the difference and more for the number of coal plants from GEO compared to EndCoal.

Another way to review these numbers is by installed capacity difference. Infographics already has this data and was stated above. Using Excel, the addition of the 1448 coal power plants' installed capacities gave a world installed capacity value of 1,237,231MW. This was expected with the incorrect number of power plants. The installed capacity of the Chinese plants and Indian plants were then found in Excel to be 161,457MW and 159,714MW respectively.

$$(935{,}427 - 161{,}475) + (214{,}490 - 159{,}714) + 1{,}237{,}231 = 2{,}065{,}959MW$$

This number now represent a more realistic installed capacity, but the fact Infographics have the United States as a stand-alone region led to the investigation of cross referencing the United States information from Infographics and GEO. According to Infographics, the United States coal powered plants have an installed capacity of 278,823MW meaning that between the United States, China and India, combined are accountable for 71.6% of installed capacity of global coal power plants.

The number of United States coal power plants has decreased in recent years and so if the GEO data is outdated slightly for the U.S, like China and India, then the joint installed capacity with Infographics should decrease and be even closer to matching with the original Infographics value. Using Excel, the total installed capacity for the United States was indeed higher than that of the Infographics total. 368,131MW was stated in GEO and so the difference between this and the 278,823MW is 89,308MW. Taking this value from the total of 2,065,959MW that was found gives a final value of 1,976,651MW. This could be an acceptable value for using in the Analysis and Results chapter as it is within one percent of the Infographics value.

$$\frac{1{,}976{,}651}{1{,}996{,}426} \times 100 \; = 99.01\%$$

Although 1,976,651MW would be an acceptable figure for the total installed capacity of all coal powered plants the important categorisation aspect is flawed but this will be addressed later.

China, India and United States, being 71.6% of the total installed capacity, have been part of severe recent changes and needed to be addressed. Having been addressed, there is now an alignment for the GEO reference but beyond alignment further validation is needed so some checks were carried out on two random countries to see if they were correct and up to date.

There are two Hong Kong coal powered stations stated within GEO as seen in table 1 which is the correct number of active coal power stations (HK-PHY, 2016). Both the design capacities are correct. (CLP, 2016) shows this for Castle Peak Power Station and (Wiki-Lamma, 2018) shows this for Lamma Coal Power Station. Unfortunately, this is a Wikipedia entry, but it was last updated in 2018 and shows the breakdown of the operation units within the plant which is three 250MW and five 350MW coal powered units which is part of an overall installed capacity of 3736MW that also uses natural gas as a fuel in other turbines.

	Power Plant Name and Country	**Design Capacity (MWe)**
1.	Lamma Coal Power Station Hongkong	2500
2.	Castle Peak Power Station (CPPS) Hong Kong	4108

Table 1 – Hong Kong Data - GEO

Mexico was also considered, and its three coal powered stations as shown in table 2. Firstly, Wikipedia was used to verify if all there was three coal powered plants in Mexico and this was proved correct (Wiki-Mexico, 2018) last updated in 2018. (Industry About, 2015) shows the correct design capacity for Plutarco Ellias Calles (Petacalco) Thermal Power Plant. (Hobby, 1994) verifies the design capacities of both Carbon I and Carbon II power stations.

	Power Plant Name and Country	**Design Capacity (MWe)**
1.	Carbon II Coal Power Station Mexico	1400
2.	Jose Lopez Portillo (Carbon I, Rio Escondido) Coal Power Station	1200
3.	Plutarco Elias Calles (Petacalco) Thermal Power Plant Mexico	2100

Table 2 – Mexico Data - GEO

While validating the GEO reference, using Hong Kong and Mexico as random examples, it is should be noted that GEO was continually appearing in the top search results.

A last reference that has a full database of power plants in the world is downloadable as an Excel file and includes renewable and nuclear power plants is from the 'World Resources Institute' (WRI), (WRI, 2018). The database has 28,865 power plants entries in total and can be manipulated just to show coal or oil or gas power plants the same as the GEO reference. On manipulating the data, to show all the coal powered plants, the installed capacity was 1,852,574MW so slightly under the installed capacity totals given by EndCoal and Infographics. This installed capacity was still closer than GEOs list. WRI therefore could be a more valid reference than GEO especially if the same cross referencing provided good verification.

In summing up, GEO is clearly varied and outdated in some instances for the list of coal power plants but the reason it is worth investigating, even with the discrepancies, is that it has separate lists for coal, gas and oil plants. These separate lists can be easily accessed and manipulated within Excel. There was some validation applied to ensure the reference was acceptable but WRI is more up to date and although it has a slightly different total installed capacity from that of Infographics and EndCoal, it is clearly more up to date then GEO with the same possibilities for Excel manipulation. Lastly, WRI consists of only active plants (Byers, 2018) whereas GEO includes shutdown/decommissioned plants in its lists. Using the same logical steps to validate the GEO reference the installed capacity for WRI comes to

2,004,432MW. Final consideration led to choosing WRI over GEO for the final analysis on coal power plants (including the cross referencing). 2,004,432MW will therefore be the total installed capacity of coal power plants worldwide used for the final analysis. Appendix A shows a sample of the list of coal power plants as given in WRI.

2.1.2 OIL POWER PLANTS

Fuel oils are the next highest CO_2 emitting fossil fuel after coal. The fluctuation of oil power plants closing, and opening is steadier than coal and so it is expected that the list of oil power plants from GEO would be more accurate. However, WRI gave a very accurate list for coal power plants and it is assumed it will do the same for oil power plants.

There are 2863 oil powered plants worldwide (WRI, 2018) with an installed capacity of 465,452MW. GEO claims there are 1071 oil powered plants worldwide with an installed capacity of 254,314MW. Further investigation will hopefully find which is likely to be more accurate.

On further inspection 1746 of these 'power plants' in WRIs database have an installed capacity under 30MW. This could come from diesel generators that are powering lowly populated and therefore low energy demand areas. Although some may be diesel generators, they will still be referred to as power plants within this project. The total of the 1746 oil power plants installed capacities (under 30MW) only amounts to 7080.6MW which is only 1.52% of the total installed capacity. This is low, but still important for the carbon sequestration aspect of the project. Even removing these 1746 'power plants' WRI would still have a much higher installed capacity than GEOs list.

Cross referencing to validate WRIs list, that is expected to be the most up to date and correct of the references, proved very difficult. Oil does not have the same stranglehold as coal in the eyes of society and this is fair when you consider the carbon emissions associated by the two fuels. Also, the installed capacities of the coal power plants are over 400% more than the oil power plants. Coal power plants produce a lot more tonnes of CO_2 than oil power plants.

The GEO reference does not have any Argentinian oil power plants within its list whereas the WRI reference has 198 oil power plants. Nine of these have an installed capacity of over

30MW so it would be expected that GEO would have at least a couple of Argentinian plants within their list. GEO shows one 25.6MW oil power plant in Namibia just showing that the reference does show power plants with installed capacity under 30MW. Furthermore, WRI shows this Namibian oil power plant and two more that have a combined installed capacity of 34.3MW. Anixas, Langer-Heinrich and Paratus are the three stated in the WRI reference and and (NamPower, 2018), (PEL, 2008) and (Industry About, 2016) respectively show cross reference to each of the three. From this, WRIs list of oil power plants, again, appears to have the most accurate information for oil power plants worldwide and will be the reference used for the final analysis.

Unfortunately, some of the oil power plants being backup generators, would only be used sparingly but will be assumed to have daily use for the project. As mentioned earlier, only 1.52% of all the installed capacity is under 30MW and so the assumption that all oil power plants are in daily use will not create much of a difference for the final analysis. Therefore, the figure of 465,452MW of installed capacity for all oil power plants worldwide will be used. A sample of all the oil power plants worldwide and their installed capacities is given in Appendix B.

2.1.3 GAS POWER PLANTS

Natural gas is the least environmentally damaging of all the fossil fuels. Countries that require high electricity supply but have been looking to move away from coal, unable to satisfy requirements with renewables, have diverted to natural gas as one of their main suppliers of electricity. The lower carbon emissions associated with natural gas have been pivotal in this movement. Nuclear power is another source of electricity, with lower carbon emissions than natural gas, that could have fulfilled this void but there has been a taboo over nuclear power particularly 5-10 years ago.

(WRI, 2018) has been considered the most reliable reference for coal and oil powered plants and hence is being used for the final analysis in these instances, it is expected that it will also be the most reliable reference for the list of gas powered plants. WRI states there are 2943 gas powered plants with an installed capacity of 1,167,790MW. (GEO, 2018) states there are 2784 gas powered plants with an installed capacity of 1,208,318MW. Maybe, out of the three power plant types, it was inevitable that GEO and WRI would have similar values for one as it does here for gas power plants. The values are within 4% of one another:

$$\frac{1,167,790}{1,208,318} \times 100 = 96.65\%$$

GEO shows some power plants that are inactive unlike WRI that only shows operating power plants. GEO shows 5 shutdown and 3 decommissioned plants so the installed capacity would actually be lower than originally stated which would mean the values for each are even closer.

Similarly to the oil powered plants data, there was a lack of information for gas powered plants worldwide and their installed capacities. Again, this is due to the much higher concerns associated with coal and its emissions over that of gas and oil. Coal powered plants total worldwide installed capacities are higher than that of oil and gas powered plants added together. With this in mind, it will be assumed fair that the cross referencing between WRI and GEO is enough validation for analysis. Like coal and oil, WRIs list will be used again for gas power plants. This means the installed capacity total of 1,167,790MW will be accepted and used for the analysis. Appendix C shows a sample of the list of all gas power plants worldwide.

2.1.4 CARBON EMISSIONS CALULATION

The sub-chapters before this, have found and validated a worldwide installed capacity total for each of coal power plants, oil power plants and gas power plants. The importance behind finding these figures are for the final emissions calculation. They need to be kept separate as each of the fossil fuels create different emissions per kilogram of burnt fuel, where coal is the worst of these.

The equation that will be used calculates how many tonnes of CO_2 is produced per year but can be easily switched to per day etc. This is used for coal, oil and gas power plants separately. By searching in google for said equation the first result was in the form of a video by ‘McHenry County College’. See Figure 5.

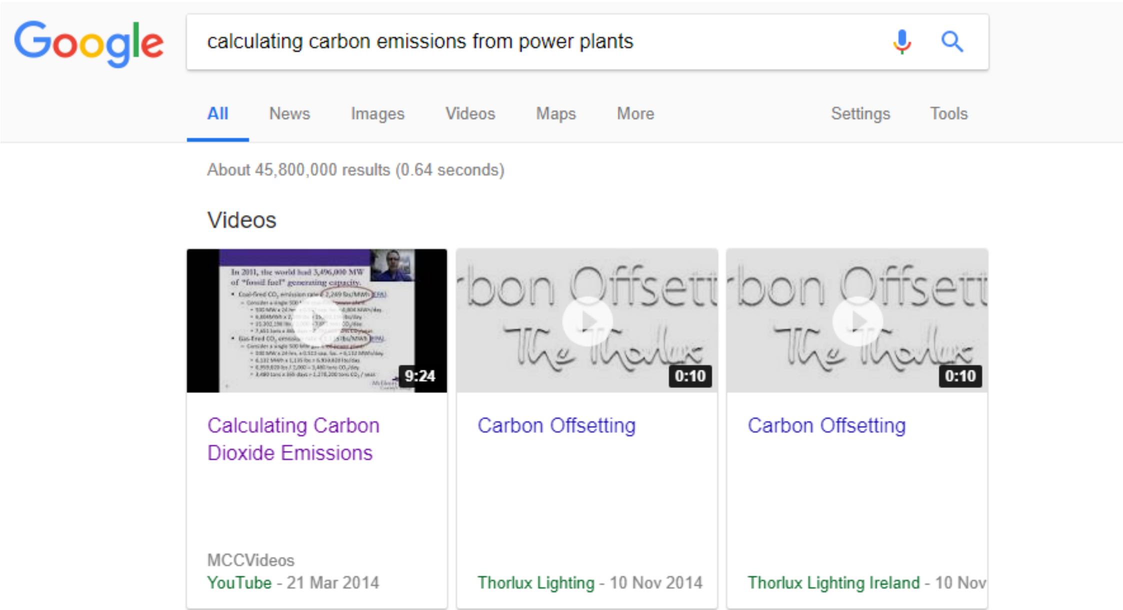

Figure 5 – Carbon Emissions Calculation Search

The reference to the video is (MCC, 2014). This is an American educational institutes video using old imperial units but will be converted to standard imperial (S.I) units for this project. Figure 6 shows a clip of the equation being used in the video for a coal powered plant of installed capacity of 500MW.

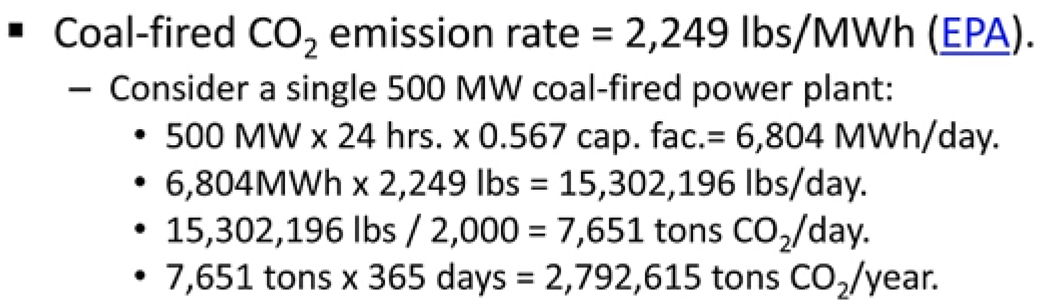

Figure 6 – MCC Carbon Emission Calculation

The changes to ensure this is used in S.I are:

- Instead of pounds per megawatt hour (lbs/MWh) we will use kilograms of carbon dioxide per megawatt hour ($kgCO_2$/MWh) for the emission rate. The ‘lbs/MWh’ above should actually have CO_2 within it so the conversion should include CO_2 and ‘$kgCO_2$/MWh’ is the correct units for emission rate.

- The third line that divides by 2,000 is to convert lbs to tons. When converting from kilograms to tonnes, there is a division of 1,000 required. So, 1,000 will be used instead of 2,000.

The equation below shows the properties required without the numbers that figure 6 has.

$$\frac{Installed\ Capacity \times\ Capacity\ Factor\ \times 24 \times Emission\ Rate}{1{,}000} \times 365 = TonnesCO_2/Year$$

The installed capacities we have found already. The emission rate is dependent on the fuel type. (Moomaw, 2011) has emission rates as grams of carbon dioxide per kilowatt hour (gCO_2/kWh) for most electricity generating fuels and values for different percentiles are available. Table 3 shows part of the table that only consists of coal, oil and gas.

Percentiles	**Coal (gCO_2/kWh)**	**Oil (gCO_2/kWh)**	**Natural Gas (gCO_2/kWh)**
Minimum	675	510	290
25^{th} Percentile	877	722	422
50^{th} Percentile	1001	840	469
75^{th} Percentile	1130	907	548
Maximum	1689	1170	930

Table 3 – Emission Rates

Converting 'gCO_2/kWh' to '$kgCO_2/MWh$' requires multiplying by 1,000 and then dividing by 1,000 meaning the units have the same value. The numbers can be taken straight from the table for the carbon emissions calculation. As this project is focusing on a worldwide scale the 50^{th} percentile values are logically the best to be used for the equation as an average. This means the emission rates are as follows:

- Coal power plants - 1,001$kgCO_2/MWh$
- Oil power plants - 840 $kgCO_2/MWh$
- Gas power plants - 469 $kgCO_2/MWh$

Referring back to the equation, the other unknown is the capacity factor. Capacity factors vary for each and every power plant and for the sake of the project an average will need to be made for each type. Figure 6 taken from (MCC, 2014) video shows a capacity factor for coal power plants of 0.567 and within this video a gas power plant is also considered, and its capacity factor is given as 0.511. The outputs from the video in $tonsCO_2/year$ for each coal and gas can then be compared using the emissions rates accepted for this project. The calculation for coal gave:

$$\frac{500\times\ 0.567\times 24\times 1{,}001}{1{,}000}\times 365=2{,}485{,}943 Tonnes CO_2/Year$$

To convert from Tonnes to American Tons you multiply by 1.1 and this would be required for a fair comparison. Therefore, the final value would be 2,734,537.3TonsCO_2/Year

$$\frac{2{,}734{,}537}{2{,}792{,}615}\times 100=97.9\%$$

The final values using the different emission rates are within 3% of one another and therefore validate the 0.567 as an acceptable capacity factor.

The same was done for the capacity factor given for gas ‘0.511’ and the calculation showed:

$$\frac{500\times\ 0.511\times 24\times 469}{1{,}000}\times 365=1{,}049{,}706 Tonnes CO_2/Year$$

$$1{,}049{,}706\times 1.1=1{,}154{,}677 Tons CO_2/Year$$

$$\frac{1{,}154{,}677}{1{,}270{,}200}\times 100=90.9\%$$

This time the two values were within 10% of one another which is still reasonable, but the values were less than half that of the coal values. Taking this into consideration, the capacity factor will be increased slightly to 0.52 for, what will be assumed to be, a more accurate and acceptable value for the final analysis.

Unfortunately, the video did not have a capacity factor for oil and oil is used as a back up source in many instances which would mean a low capacity factor. It was earlier stated that oil power plants would have daily use. Giving a capacity factor slightly under the one given from gas would be a fair assumption and so a value of 0.5 will be used for oil in the analysis. The capacity factors that will be used in the final analysis are:

- Coal power plants - 0.567
- Oil power plants - 0.5
- Gas power plants - 0.52

The unknowns now have average values that can be used in the carbon emissions calculation for the final analysis.

2.2 CARBON SEQUESTRATION

CO_2 is understandably the biggest concern of all the GHGs with regards to global warming. The sheer amount of CO_2 outweighs all other GHGs. The focus of this project is on FFPPs and their carbon emissions, so how the power plants produce the carbon must be considered.

FFPPs emit gaseous products including GHGs together as ‘flue gas’ that exits the plant via a flue (exhaust pipe) after the combustion of the fuel (Perry, 1997). The exact composition of the flue gas differs slightly in each plant and differs depending on which fossil fuel is combusted but in the context of the world they are reasonably similar. The amount of CO_2 within the flue gas is much more than that of the other GHGs within its composition. Other GHGs include sulphur oxides, nitrogen oxides and particulate matter. These GHGs are a very small percentage of the overall composition and can be treated on site in a few ways. One example of this is, ‘flue gas desulfurization’ that removes the sulphur dioxide from the flue gas by using lime to capture it (NLA, 2018). The sulphur dioxide can then be reused in different ways.

CO_2 may have the largest proportion of the GHGs within the flue gas but it is not the highest proportion of the gases it is composed of. Nitrogen makes up the majority of the composition. It occurs highly due to the combustion with air. Oxygen and steam are two other elements within the composition. Steam is what can be physically seen exiting the stack and creates the classic image associated with FFPPs, see Figure 7 (Letzter, 2016).

Figure 7 – Flue Gas Exiting a Power Plant

Having identified the carbon emissions are part of a wider composition known as flue gas, the carbon sequestration aspect can be considered. Flue gas is rejected at high temperatures from the exhaust and can also be known as 'waste heat'. There are different ways that the waste heat can be reused in combined cycles and such but there is always the rejection of the carbon emissions continuously while the FFPPs are in use.

The carbon sequestration can be done within the exhaust pipe where the carbon is sequestrated and captured to be sent elsewhere, like stored deep under the earth's surface in rocks (Wang, 2017). A more productive way to sequestrate the carbon would be to send the flue gas and all its elements through the exhaust pipe to a sequestration technology that captures the carbon from the mix of elements naturally. The other GHGs involved could pose a problem with this, especially in higher installed capacity power plants. The acidic properties can have a negative effect but if there is a low enough quantity of these elements it could be possible to pipe the flue gas straight to the carbon sequestration technology. (Zhang, 2015). Grouping the installed capacities in different categories takes this into consideration.

Overall, the other GHGs can be treated by other methods like the flue gas desulfurization mentioned before. Figure 8 shows a basic schematic of the flue gas being converted to the point where the CO_2 can be captured for sequestration (NETL, 2018).

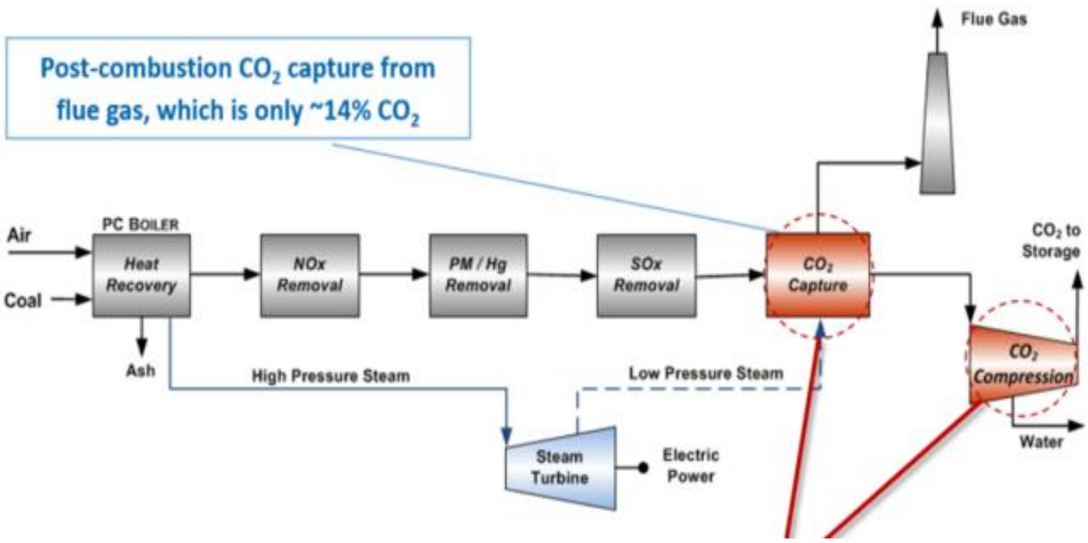

Figure 8 – Separation of Flue Gas

2.2.1 MICROALGAE TECHNOLOGIES

This project looks to utilise microalgae as the technology for carbon sequestration from FFPPs. It can be used in a few different ways. Microalgae cells need to be immersed in water due to the growth requiring photosynthesis. The cells sequestrate the CO_2 stopping it from reaching the atmosphere. Before discussing the technologies, it should be mentioned that microalgae can still sequester carbon and grow in wastewater so fresh water is not required (Kadir, 2018).

There are hundreds of thousands of types of microalgae (Guiry, 2012) which have varied uses but their cell composition is the same throughout. This means that for carbon sequestration the type of microalgae cell does not have influence on this project (Li, 2013). This would only be of importance if there was a strategy to incorporate cell types with cell uses for specific countries and their requirements, be it social or economic requirements.

There are numerous factors that can affect the growth rate of microalgae. For this project, only the factors that have a pivotal effect on the amount of carbon sequestered will be considered. Unfortunately, this will lead to uncertainties in the final analysis, but the global values will still paint a valid picture for discussion.

Flue gas and its composition has been mentioned and the GHGs other than CO_2 can influence the growth of the microalgae. This is because the acidity of these GHGs can cause an imbalance on the PH of the water and if the ponds PH becomes too imbalanced the microalgae cells can die (Ying, 2014). Higher installed capacities will produce larger amount of these acidic GHGs, but larger ponds will be able to cope with this (with an even spread of composition throughout the ponds) and that is why categories will need to be created for 'pond size vs installed capacities vs FFPP type'. So, size of pond/amount of water and component to spread evenly the composition are significant factors (Zhang, 2015). The amount of CO_2 needed to grow the algae is of concern and to produce 1 tonne of microalgae 1.83 tonnes of CO_2 is required (Li, 2013). Light is required to help the microalgae absorb the CO_2 and this means that all the CO_2 from the flue gas cannot be absorbed. Day and night therefore have an affect on how much CO_2 is sequestered (Valdes, 2012). Artificial lighting could be used to counter this, but the energy required to power lights increases the demand further. Artificial light would drive costs up. Climate conditions, i.e. daylight hours would want to be factored in as two groups where exposure to daylight is either high or low depending on the country but the process of reviewing the thousands of power plants to decide which plant would fall into which category would be too exhaustive.

Microalgae naturally sequestrates carbon, so the technologies used for cultivation is the same as the technologies used for carbon sequestration. The first technology in which microalgae can be used in this way is in an open pond. This is the most commonly used commercialised technology to cultivate microalgae and is better used as a raceway pond (RWP) (AAA, 2015). The difference between a RWP and regular pond is the paddle wheel to spread everything evenly. 'MicroBio Engineering' is a company that sells microalgae raceway ponds and Figure 9 shows a built RWP (MBE, 2018).

Figure 9 – Microalgae Raceway Pond

The other commercialised microalgae cultivation technology is a closed technology. Closed photobioreactors (PBRs) come in different forms but are generally glass tubes, consisting of the water and microalgae cells, ordered in a sound formation like a horizontal formation (Oilgae, 2018). 'Varicon Aqua' are a company that sell PBRs and Figure 10 shows an example of a PBR used for microalgae cultivation that they sell (VA, 2018).

Figure 10 – Microalgae Photobioreactor

Linking these technologies to FFPPs for carbon sequestration can be summarised in an image similar to 'Figure 8 – Separation of Flue Gas'. Figure 11 shows a detailed example of microalgae used for carbon sequestration (Zhang, 2015).

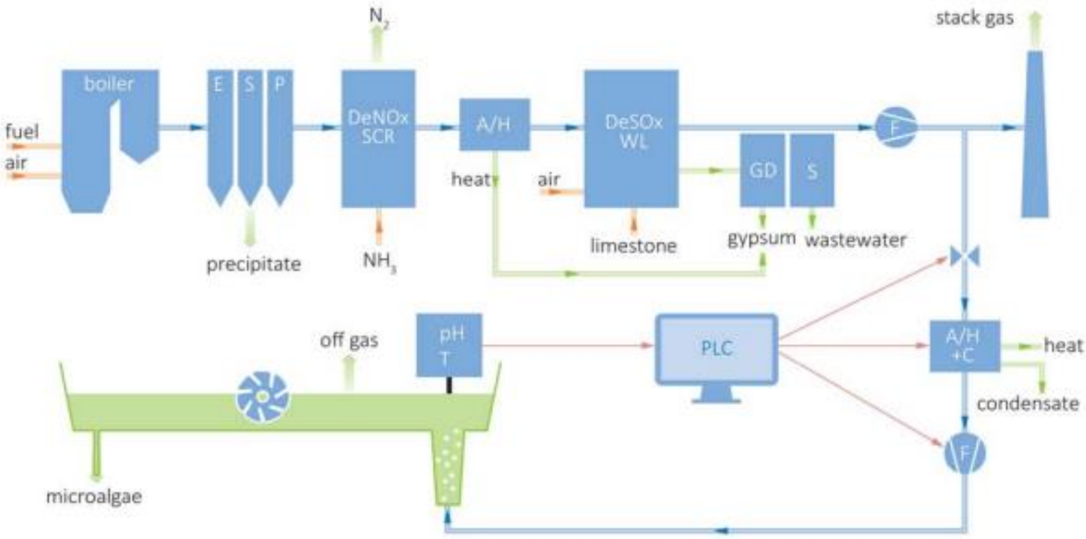

Figure 11 – Flue Gas to Microalgae

The two commercialised microalgae cultivation/carbon sequestration technologies will now be considered in more detail to help select which will be the best technology for this project.

2.2.1.1 RACEWAY PONDS

Most of the literature surrounding this area looks to utilise the microalgae, mainly for biodiesel production, once it is cultivated and the focus is on ensuring the cultivation is completed in a controlled process like that in Figure 11. The focus on this project however is on the CO_2 sequestration and the effect microalgae as a mitigation technology can have on a global scale, where all FFPPs are piping their carbon to this microalgae technology. There is the potential to sequestrate up to 80-99% of CO_2 from flue gas within a microalgae RWP but a 3600 acre pond would be needed for a gas power plant of installed capacity 200MW and a 7000 acre pond would be needed for a coal power plant of installed capacity of 200MW (Sayre, 2010). These ponds would be sufficient to sequester 80% of CO_2 from each power plant. There is no depth stated for these ponds and the type of pond will be assumed to be RWP. These references can be utilised for the final analysis.

Microalgae RWPs are much more efficient than just a normal pond that does not have the paddle wheel. The paddle wheel is important for evenly distributing anything within the pond to avoid build ups in one location (Costa, 2014). This helps to keep the PH balance constant throughout the pond stopping any of the microalgae cells dying. RWPs can also be easily scaled up which is good for the varied installed capacities that the power plants have (Cheng, 2015).

RWPs exposure to little light during the night, unless artificial light is used leads to the release of CO_2 from microalgae cells. This release would lead to decreased efficiency and decrease in possible carbon sequestrated. RWPs can be covered by a lid overnight keeping the CO_2 recycled within the pond until the daylight hours (Costa, 2014). The CO_2 losses are to allow oxygen to the ponds. The lid can be used for a greenhouse effect during the day to improve microalgae growth rate, if that was of interest. Placing a lid on just for overnight, would require extreme engineering capability if used on a huge RWP. If the RWP was lidded all the time then the greenhouse effect would mean temperature would become a more influential factor and as temperature is not in the analysis due to its complication when considering thousands of power plants, a closed RWP will not be used.

(Cheng, 2015) investigated a 1191m^2 raceway pond linked to the flue gas pipe of a coal power plant with installed capacity of 500MW. The aim of that project was on improving growth rate of microalgae and not sequestrating CO_2. It is not clear how much CO_2 is sequestered as it is not the aim of the project however it mentions $100m^2$ RWPs have had depths of 1m and so the depth can vary depending on surface area of the RWP but beyond 1m is possible.

What is important is how much microalgae a microalgae RWP can hold. As stated in the sub-section before it takes 1.83Tonnes of CO_2 to grow 1Tonne of microalgae. The analysis and results will extrapolate this data to pond size, but when the pond is full poses a problem. This stage is not totally evaluated because the most important aspect of the project is sequestrating carbon. For example, if the pond was full within a week then most of the cells would need to be emptied every week which would not be ideal. Table 4 shows some of the opportunities other than bioenergy for microalgae when it needs to be harvested (Sayre, 2010).

Algal carbon capture and sequestration systems	Advantages	Liabilities
Permanent burial of total fresh biomass	Captures the most carbon No biomass processing	Burial of inorganic nutrients and water in biomass
Permanent burial of algal lipids	No loss of inorganic nutrients Long-term energy reserve Easily handled as liquid	Sequesters < 50% of carbon present in biomass Energy costs associated with biomass processing
Soil amendment with algal biochar	Potential soil supplement Permanent carbon sequestration without burial	Sequesters less than 55% of carbon present in biomass Energy costs associated with biomass processing Potential dispersal of some fraction of inorganic nutrients

Table 4 – Microalgae Pond Removal Uses

Once the microalgae has to be harvested, losing as little carbon to the atmosphere would be of most importance in the outline of this project even although this goes outwith the scope slightly but if a focus was placed on this, Table 4 shows some of the least carbon producing ‘uses’ of the microalgae once harvested. ‘Uses’ is written like so because the microalgae is not really being used as productively as it could be. The burying is optimal for minimising carbon emissions once harvested.

Table 5 shows the important factors that contribute to the carbon sequestration as stated in the ‘microalgae technologies’ and how RWPs link to these factors.

Factor	Does RWP meet this? (✔/✘)
Sequestrate CO_2 efficiently	✔
Cater to power plant fuel types	✔
Cope with flue gas composition	✔
Easily scalable	✔
Light distribution and changes	✔

Table 5 – Carbon Sequestration Factors (RWP)

2.2.1.2 PHOTOBIOREACTOR

Having reviewed RWPs as a microalgae technology for the final analysis and it ticking all the boxes, it is logical to expect that PBRs will not be used. The literature around PBRs will still be reviewed culminating in the same ‘tick/cross’ carbon sequestration factors table.

The first major difference between the two microalgae technologies is the RWPs are an open and technology and the PBRs are closed technology. Microalgae in a closed technology is exposed to a greenhouse effect and therefore the cells grow at a quicker rate (Ugwu, 2008). In this project, the slower the microalgae cells cultivate the better as long as they are sequestrating acceptable amounts of carbon.

Large scale PBRs are difficult to deploy and the build up of microalgae cells in tubes means harvesting every other day (Chen, 2011). Scaling up can only go so far due to the complicatedness. The required harvesting rate is one of the integral factors to choosing RWPs over PBRs. The flue gas needs to be spread between numerous tubes and the split between these tubes will not be even. This means some tubes will have an imbalance in PH unless the pre-treatments of the flue gas to rid of other GHGs is completed which would add costs. Lastly, the light distribution is not even due to the cylindrical tubes (Chen, 2011).

Some of the advantages of PBRs over RWPs are less CO_2 loss and a higher quality of control due to multiple tubes (Singh, 2012). The loss of CO_2 is due to the enclosure and the lid on an RWP can replicate this, but more importantly can handle the composition of the flue gas unlike PBRs. RWPs are just controlled by paddle wheels. Lastly, the necessity for harvesting quickly means that something must be done with the microalgae, i.e. burying it. As seen in

Table 4 in the RWP sub-section this leads to CO_2 emissions and so PBRs in this project actually have higher CO_2 loss.

Table 6 shows the important factors that contribute to the carbon sequestration as stated in the 'microalgae technologies' and how PBRs link to these factors, similarly to Table 5.

Factor	**Does PBR meet this? (✔/✖)**
Sequestrate CO_2 efficiently	✔
Cater to power plant fuel types	✔
Cope with flue gas composition	✔ with pre-treatment
Easily scalable	✖*
Light distribution and changes	✖

Table 6 – Carbon Sequestration Factors (PBR)

*PBRs are scalable but not easily scalable compared to RWPs

Microalgae RWPs will be selected for the final analysis in combining with all FFPPs worldwide for carbon sequestration.

2.2.2 OTHER TECHNOLOGIES

Reviewing the literature on other carbon sequestration technologies allows for evaluation and comparison in the final analysis. The key aspect of the sub-section is to find how much carbon they can sequestrate, and the technologies considered will be post combustion of the fossil fuel, the same as the microalgae technologies.

The first carbon sequestration technology is a technology similar to the technologies used for sequestrating the other GHGs in flue gas. Flue gas desulfurization was mentioned before and it treats the sulphur within the exhaust pipe. This technology would also occur in the exhaust pipe and is known as 'ammonia scrubbing'. Ammonia's chemical formula is NH_3 and Figure 12 shows a basic diagram of ammonia scrubbing for CO_2 removal (Peltier, 2008).

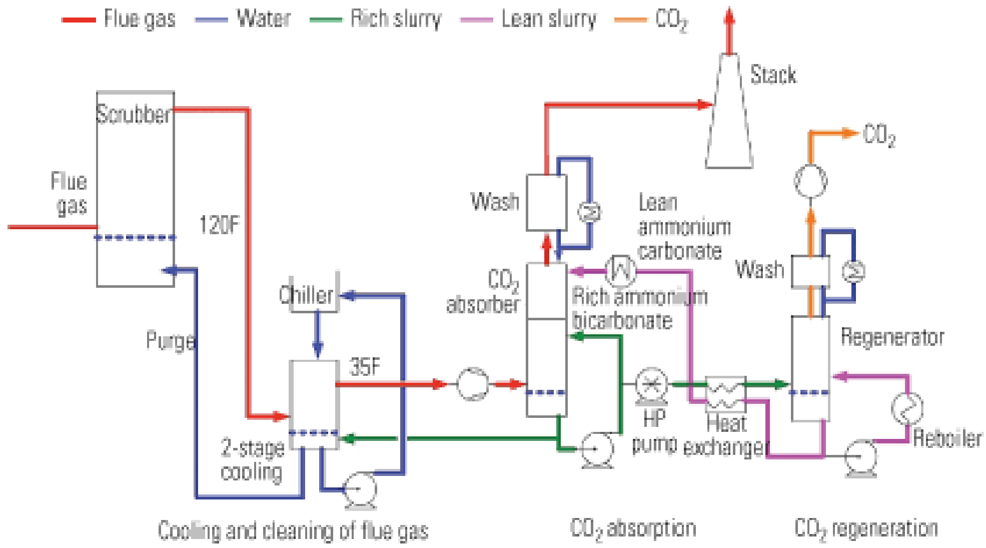

Figure 12 – Ammonia Scrubbing for Carbon Sequestration

The most important aspect with ammonia scrubbing of flue gas for carbon sequestration is temperature and this can be recognised in Figure 12. With the right temperature, the ammonia scrubbing can reach up to 99% sequestration of CO_2 (Diao, 2004). Figure 13 shows the graph of CO_2 removal efficiency over time showing the 99% reach (Diao, 2004).

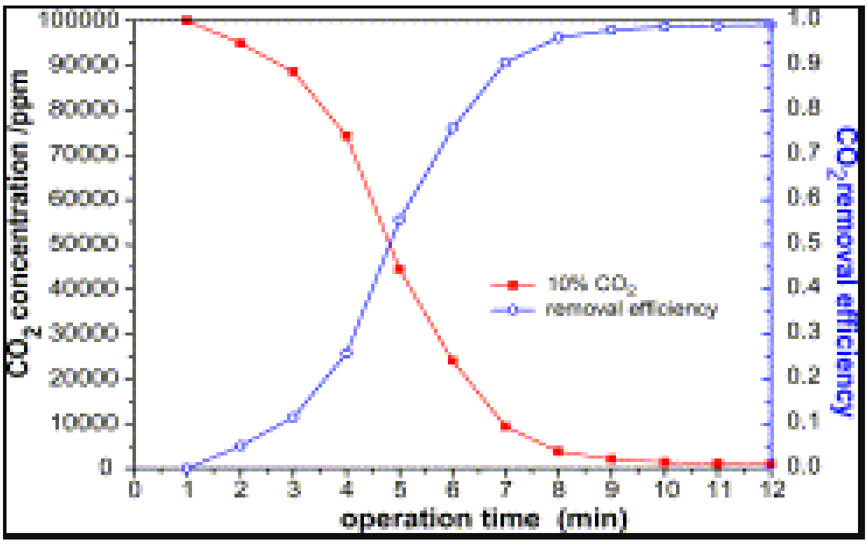

Figure 13 – Ammonia Scrubbing CO_2 Removal Efficiency

The ammonia scrubbing quickly gets to work on sequestrating the CO_2 but perfecting the conditions in which to do so is a difficult and expensive task. More importantly, for high installed capacity power plants that would require vast amounts of ammonia, to sequestrate high percentages of carbon, present environmental risk. It's toxic properties present environmental risk and has corrosive properties which creates risk to the power plant. Or, the ammonia would need to undergo waste disposal which can pose more environmental impact and human reaction with high exposure to ammonia can cause health concerns (Zisopoulos, 2018).

Another carbon sequestration technology, which is similar to the ammonia scrubbing is 'amine scrubbing' also known as 'amine gas treating'. Effectively it works the same as ammonia scrubbing but the focus is on gas power plants (Rochelle, 2009). It uses amines such as 'monoethanolamine' and 'diethanolamine' (Rochelle, 2016). Figure 14 shows the basic process of amine scrubbing (Sassi, 2008).

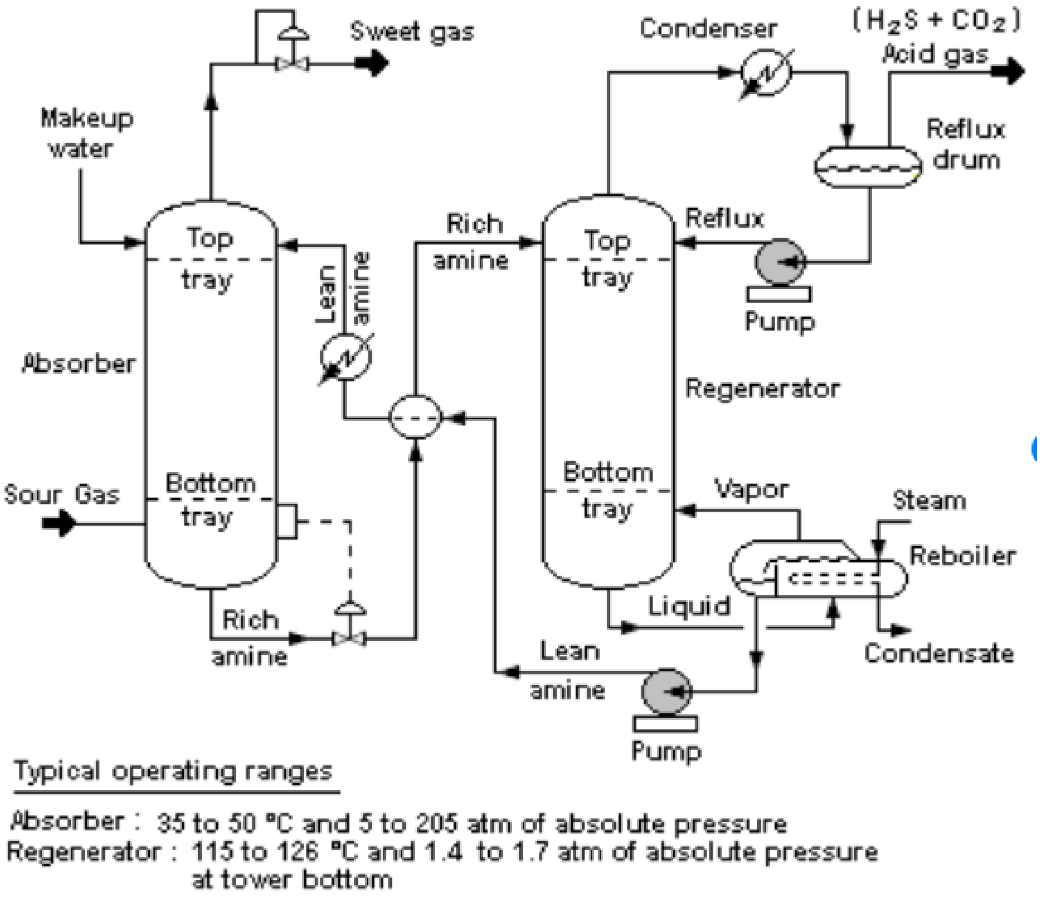

Figure 14 – Amine Scrubbing for Carbon Sequestration

Once again, the temperature needs to be controlled for amine scrubbing. The amines can remove other GHGs at the same time in high quantities but specifically for CO_2 up to 90% can be sequestered (Rochelle, 2016). The amine scrubbing can lead to corrosion like the ammonia scrubbing. High costs are also a problem (Mafra, 2018). Regular storage would be required of the CO_2. Storing CO_2 underground in geological formations lead to the release of CO_2 overtime so the percentage efficiencies of 99% and 90% for ammonia and Amine scrubbing respectively need to be considered sceptically, especially considering the rate of which the storage would be required.

2.3 ECONOMICS

The four carbon sequestration technologies explored in the literature review will be analysed in an economic sense. These four technologies are:

- Microalgae Raceway Pond
- Microalgae Closed Photobioreactor
- Ammonia Scrubbing
- Amine Scrubbing

There will be a range of fluctuating maintenance costs. This is the same for all of the carbon sequestration technologies. For the microalgae technologies, the harvested microalgae would preferably be buried for the least release of carbon emissions but from an economic point of view it would be sold. The focus would be on the cell type of microalgae, quickest growth rate and more. Using the CO_2 produced from power plants to enhance/assist growth could still present economic advantage but the other GHGs in flue gas would most likely need to be removed which would heavily drive up costs to assure that just CO_2 was being delivered.

An in-depth economic analysis of these technologies presents a vast challenge particularly within this project, so it needs to be simplified for analysis. The focus will be placed on capital costs associated with each technology.

Before separating the technologies, the cost of land needs to be considered. Once again this is a very subjective area but \$3.55 per m^2 or £2.78 per m^2 of land will be the cost used taken from a journal article focusing on the financial side of algae (Richardson, 2014). Land cost would be required for installing microalgae technologies.

A microalgae RWP has a basic structure as shown in Figure 15 (Chanakya, 2012).

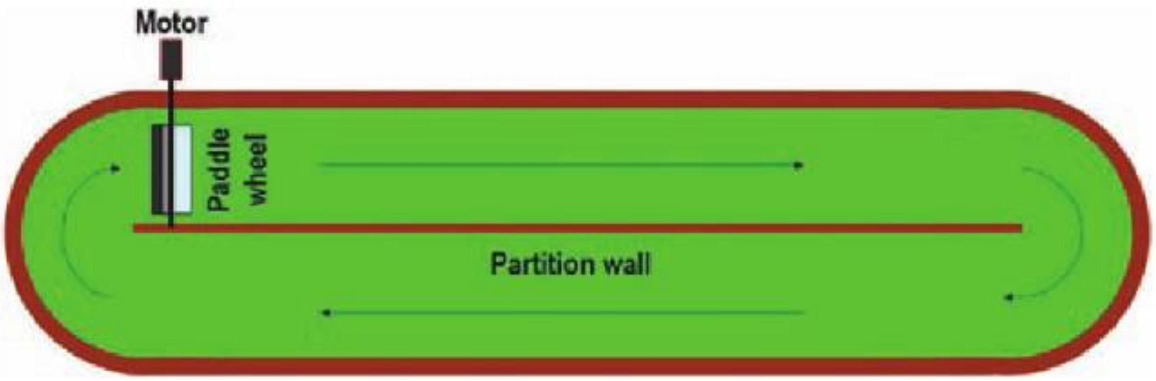

Figure 15 – Microalgae RWP Structure

RWPs have only a few components and these components are reasonably basic and accessible. Naturally, the construction costs associated are therefore low. The total capital cost, with all aspects included for constructing a RWP, except the land cost, can be estimated as $144,380 per hectare (Chisti, 2016). A hectare is 10,000m^2 and $144,380 is £113,130 using an exchange rate of 1 United States Dollar to 0.78 Pound Sterling. This was taken straight from a google search as seen in figure 16 (Google, 2018). So, the capital cost of a microalgae RWP is £11.33 per m^2. The cost per m^2 is required to work out capital costs of different sized RWPs.

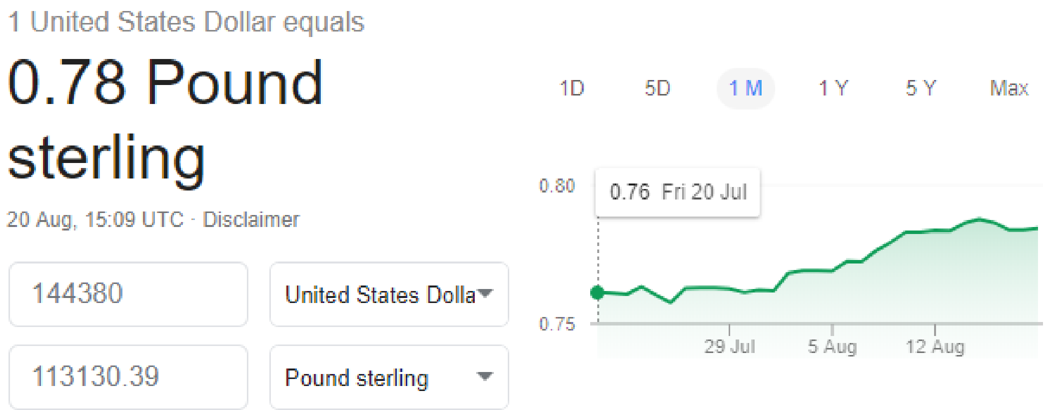

Figure 16 – Dollars to Pounds Conversion

Microalgae PBRs are also reasonably basic in components for construction. Microalgae cultivation occurring naturally through photosynthesis means that it can grow and thrive in basic environments as long as it can photosynthesise. This is clear with the two microalgae technologies. A microalgae PBR would use less land but cost more to install. (Tredici, 2016) considers a microalgae PBR, of eight modules, for a 1 hectare area. Within the analysis the costs associated for all aspects are considered and the direct capital costs were found to be €1,345,497. This is £1,205,578 using an exchange rate of 1 euro to 0.9 pounds sterling taken from (Google, 2018) in the same manner as Figure 16. The capital cost of the PBR per square metre would work out as £120.56per m^2.

Ammonia and Amine scrubbing do not require land space but would need to be used daily and the CO_2 would need to be stored/sold every day. There will need to be several assumptions to compare the four technologies in the analysis. Amine and Ammonia scrubbing are very similar technologies, but Amine scrubbing is much more common than Ammonia scrubbing for CO_2 sequestration. Ammonia scrubbing is used more often for sequestrating other GHG emissions, i.e. sulphur dioxide (Resnik, 2004).

A cost per ton of CO_2 sequestrated was found for ammonia scrubbing. This considers the material costs of getting the CO_2 sequestered and not the post capture costs. The cost per ton of carbon sequestered was found to be $47 (MPS, 2004). This reference is from 2004 unlike the two microalgae references that were both 2016. An inflation calculator was used to find the inflation from 2004 to 2016 which a clip of can be seen in Figure 17 (CPI, 2018).

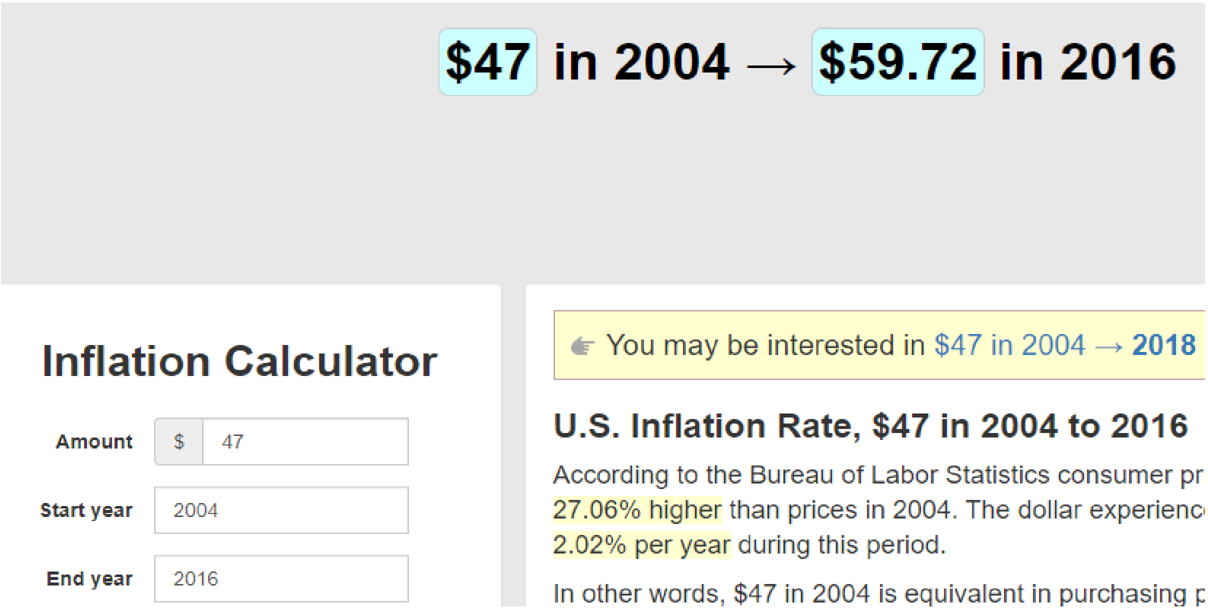

Figure 17 – Inflation Calculator

$59.72 dollars is equal to £46.71 (Google, 2018) and so the capital cost of using ammonia scrubbing for carbon sequestration is £46.71 per Ton. To change from American Ton to S.I Tonne there is a multiplication of 0.907 to be made. The final value to be used in the analysis would therefore be £42.37 per Tonne of carbon sequestrated.

Different amines can be used for the CO_2 sequestration but the one used in the specific reference to find costs associated with Amine scrubbing was 'piperazine'. (Rochelle, 2016) states that the minimum cost is $35 per Ton of CO_2 sequestered for amine scrubbing. This is at a specific pressure and the graph that this value comes from is shown below in Figure 18 (Rochelle, 2016).

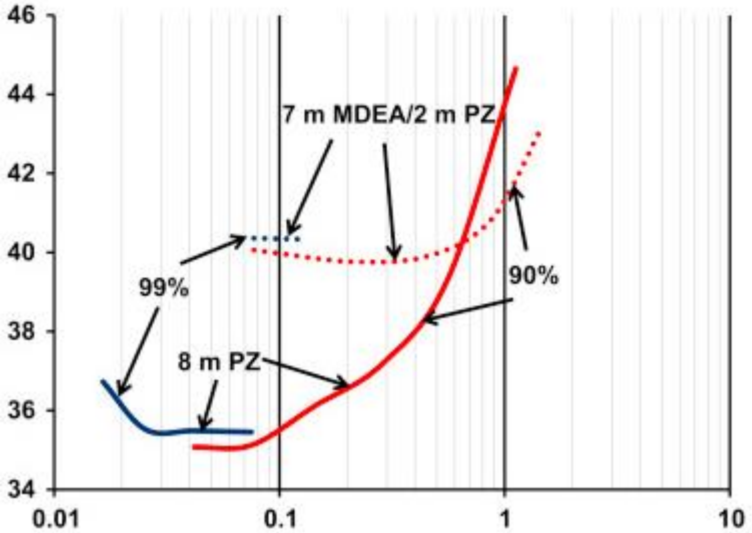

Figure 18 – Amine Scrubbing Price Variation

Using more of the piperazine can reach high percentages of CO_2 sequestered up to as high as 99%. This is under perfect conditions and varies for installed capacity of the power plant and fuel type so with this in mind an average value from the graph will be used for the cost associated with amine scrubbing. $40 per Ton of CO_2 sequestered will be the value used. Being slightly cheaper than the ammonia scrubbing was to be expected as amine scrubbing is used more so than ammonia scrubbing for CO_2 sequestration. The reference is from 2016 and so no need to review inflation just need to convert to pound sterling and S.I units. The final value is found to be £28.35 per Tonne of CO_2 sequestrated.

3 METHODS

This chapter explains the logical path that the Analysis and Results chapter will follow. The methods and materials to be utilised will be highlighted. Objectives from the project aim have been considered and so there are three sub-sections in this chapter capturing these objectives. Figure 19 shows an overview of the Methods.

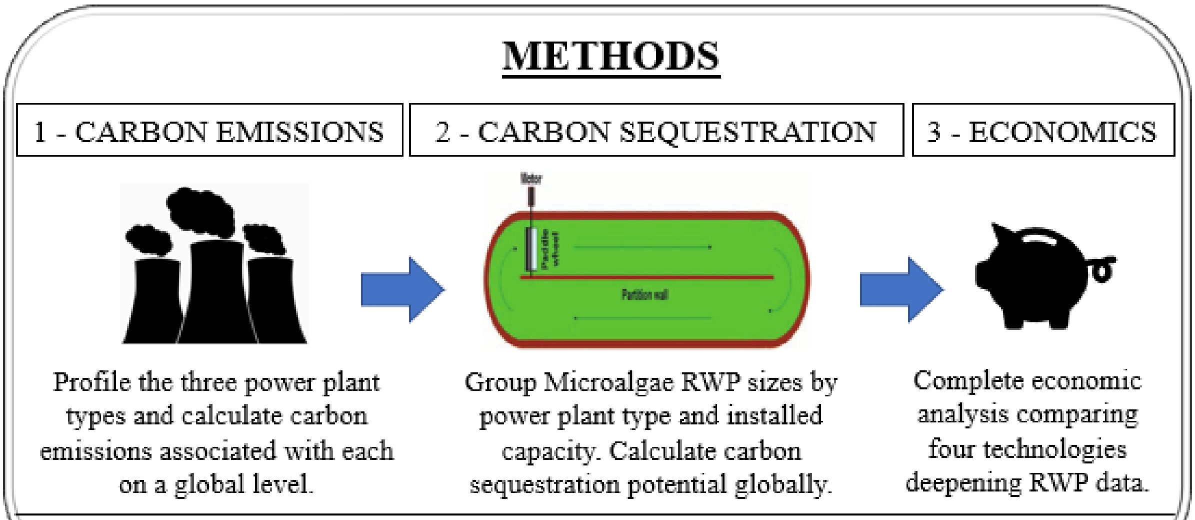

Figure 19 – Methods

3.1 CARBON EMISSIONS METHODS

With the separate lists for all global coal, oil and gas power plants attained (samples of each shown in the appendices) the data associated with them can be utilised for analysis. The different fossil fuels will be separated at first for the analysis. Each power plant has its own installed capacity data and this data can be manipulated in Excel. The capacity factors averages were found in the literature and combining this with the installed capacity data, the Emissions Calculation to calculate the total CO_2 emissions for each of the different FFPPs can be completed.

A profile is then created for each power plant type separately and combined. A clearer picture of carbon emissions by fuel type worldwide is discussed. This leads into the carbon sequestration calculations.

3.2 CARBON SEQUESTRATION METHODS

Four categories for ranges of installed capacities will be assembled using key literature to help. The categories will be kept constant through each power plant type. A large focus will be placed on coal power plants first and an average microalgae RWP size for each category will be calculated. The rate that microalgae will require to be harvested will help define the size of the RWP calculated.

Keeping the rate of microalgae harvested constant for the categories, the size of RWP for each category can then be calculated for oil and gas power plants respectively. Comparisons can then be made between the power plant types and the RWP sizes. This can be stacked against the rate of harvesting the microalgae furthering the analysis and results.

A final discussion evaluating the findings of this sub-section can then be completed.

3.3 ECONOMICS METHODS

The literature review found data for the capital costs associated with four different carbon sequestration technologies. Focusing on the microalgae RWPs, the economic data found for the RWPs can be correlated with the results found in the carbon sequestration section. This can then find the costs associated with using microalgae RWPs, linked to all FFPPs in the world, as set within the carbon sequestration section where there were categories set. The results for this can be evaluated referencing the other technologies. Lastly, a discussion and final comparison of all carbon sequestration technologies considered within this project can be completed.

4 ANALYSIS AND RESULTS

This chapter completes the path that the Methods chapter outlines and gives the numerical data involved. The numerical data will be discussed throughout the chapter and finally the aim of the project will be met.

4.1 CARBON EMISSIONS ANALYSIS

Linking back to the first sub-chapter of the literature review, the data for calculating total carbon emissions associated with each type of fossil fuel was assembled. The first calculation that can be made will find the total carbon emissions globally associated with each fuel type.

The equation for calculating global carbon emissions per year is:

$$\frac{Installed\ Capacity \times\ Capacity\ Factor\ \times 24 \times Emission\ Rate}{1{,}000} \times 365 = TonnesCO_2/Year$$

The carbon emissions per year and per day for all **coal power plants** worldwide are:

Installed Capacity - 2,004,432MW

Capacity Factor - 0.567

Emission Rate - 1,001kgCO_2/MWh

$$\frac{2{,}004{,}432 \times 0.567 \times 24 \times 1{,}001}{1{,}000} \times 365 = 9{,}965{,}809{,}243 TonnesCO_2/Year$$

Or 9.97GtCO_2/Year which is 30.68% of the energy related carbon emissions produced per year (32.5GtCO_2/Year).

Daily, this is 27,303,587Tonnes of CO_2 being produced from 2165 coal power plants worldwide.

The carbon emissions per year and per day for all **oil power plants** worldwide are:

Installed Capacity – 465,452MW

Capacity Factor - 0.5

Emission Rate - 840kgCO_2/MWh

$$\frac{465{,}452 \times 0.5 \times 24 \times 840}{1{,}000} \times 365 = 1{,}712{,}490{,}998 Tonnes CO_2/Year$$

Or 1.71GtCO_2/Year which is 5.26% of the energy related carbon emissions produced per year (32.5GtCO_2/Year).

Daily, this is 4,691,756Tonnes of CO_2 being produced from 2863 oil power plants worldwide.

The carbon emissions per year and per day for all **gas power plants** worldwide are:

Installed Capacity – 1,167,790MW

Capacity Factor - 0.52

Emission Rate - 469kgCO_2/MWh

$$\frac{1{,}167{,}790 \times 0.52 \times 24 \times 469}{1{,}000} \times 365 = 2{,}494{,}853{,}477 Tonnes CO_2/Year$$

Or 2.49GtCO_2/Year which is 7.66% of the energy related carbon emissions produced per year (32.5GtCO_2/Year).

Daily, this is 6,835,215Tonnes of CO_2 being produced from 2943 gas power plants worldwide.

Combined FFPPs are creating:

$$30.68\% + 5.26\% + 7.66\% = 43.60\%$$

Of carbon emissions associated with the energy related sector.

The literature found that 25% of all global carbon emissions are from heat and electricity production and the addition of each type of power plants carbon emissions gives a total of

14,173,153,720TonnesCO_2/Year or 14.17GtCO_2/Year. So, 25% of global carbon emissions is the maximum that can be sequestrated which is 43.6% of all energy related carbon emissions.

What was also clear in the literature review was how drastic an effect coal power plants were having globally over that of the other fossil fuels and this held true as the 5,806 combined gas and oil power plants are only producing:

$$\frac{1.71 + 2.49}{14.17} \times 100 = 29.64\%$$

So, over two thirds of the emissions are created from the 2165 coal power plants which is only 27% of the FFPPs in the world, Figure 20. Clearly the coal power plants are the biggest concern which mirrors the literature review findings.

Charting the power plants gives a better picture of the spreads between each fuel type. Figure 20 shows the proportion of type of power plant by fuel. Figure 21 then shows the carbon emissions associated with each power plant type worldwide.

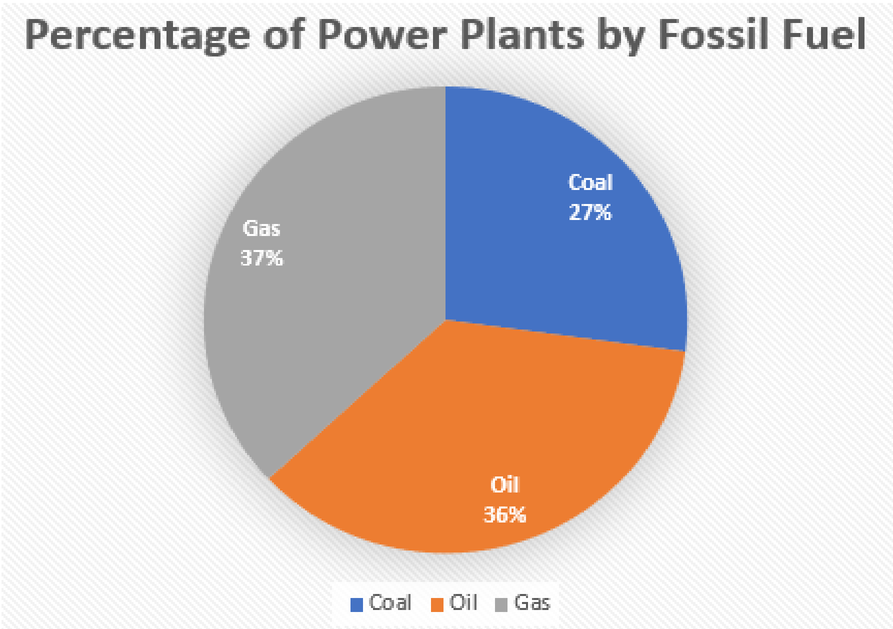

Figure 20 – Percentage of Power Plants by Fossil Fuel

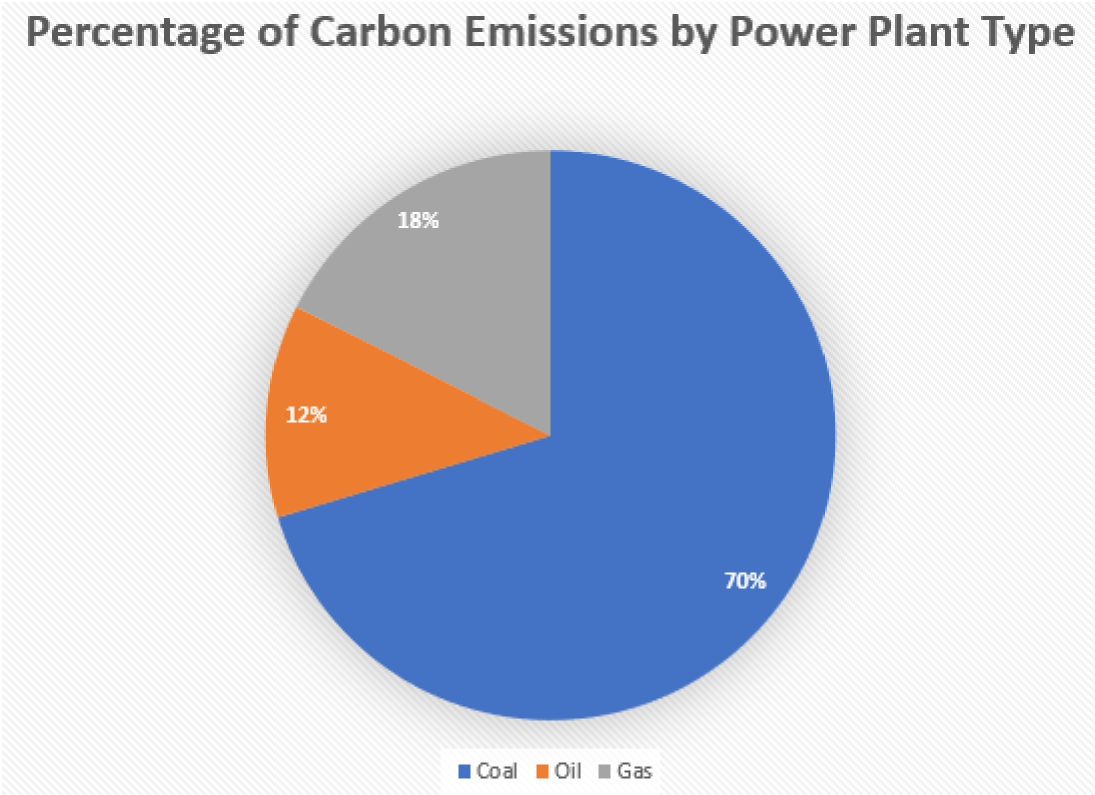

Figure 21 – Percentage of Carbon Emissions by Power Plant Type

Extending from this, China and India had around 57% of the installed capacity of coal power plants.

$$\frac{9.97\mathrm{Gt}CO_2/\mathrm{Year} \times 57\%}{14.17\mathrm{Gt}CO_2/\mathrm{Year}} \times 100 = 40.11\%$$

So, 40.11% of the total carbon emissions from FFPPs come from India and China's coal power plants alone, without including oil or gas. This is a huge percentage and helps to understand how large an effect one or two areas can have globally.

Profiling the FFPPs around the world, although there are assumptions and uncertainties, and analysing the carbon emissions associated shows the importance for carbon sequestration directly from FFPPs. Realistically FFPPs are going to play a huge part in supporting energy supply worldwide in the coming decades so exploring technologies to sequestrate the large carbon emissions created by these plants is required. From a worldwide focus, down to one small power plant or anything in-between, research and development in this area is worth investigation particularly in the near future.

Before moving to the carbon sequestration analysis, the reference for the microalgae RWPs in chapter 2.2.1.1 can have the carbon emissions calculated ready for the sequestration calculations. Table 7 shows the properties of said RWPs, but the size was given in acres. This has been converted to m^2.

	Power Plant Type	Installed Capacity (MW)	RWP size (m^2)	CO_2 Sequestrated (%)
Ref 1	Gas	200	14,569,000	80
Ref 2	Coal	200	28,328,000	80

Table 7 – RWP Reference Properties

Completing the carbon emissions calculation for these references can show the amount of carbon that would be produced in a day for each power plant.

The gas power plant would produce:

$$\frac{200 \times 0.52 \times 24 \times 469}{1{,}000} = 1{,}170.6 Tonnes CO_2/Day$$

Where 936.48Tonnes of CO_2 would be sequestered per day.

The coal power plant would produce:

$$\frac{200 \times 0.567 \times 24 \times 1{,}001}{1{,}000} = 2{,}724.3 Tonnes CO_2/Day$$

Where 2,179.44Tonnes of CO_2 would be sequestered per day.

4.2 CARBON SEQUESTRATION ANALYSIS

The appendices show the full lists of all FFPPs in the world, each list separated by fossil fuel type. Each list in the appendices is tabulated and the order is alphabetical by which country the plant is from. Within Excel, the order can easily be changed, and the lists can be manipulated more effectively.

Before grouping the installed capacities of the power plants, the key references need to be investigated further. The literature review found there were so many factors that can influence the CO_2 sequestrated but one thing that was clear for analysis was that 1.83Tonnes of CO_2 is needed to produce 1 tonne of microalgae. The microalgae start in a solution with water ready to sequestrate the CO_2 and 1 tonne of microalgae can grow in 1 cubic metre of RWP but of course the paddle wheel keeps it moving to stop any build ups. If all RWPs were deeper than 1m, leaving a clearance at the bottom of the pond, then the amount of microalgae that can be cultivated before it needs to be harvested can be calculated.

It must first be stated that CO_2 is not captured instantly by the microalgae. Some CO_2 escapes to the atmosphere before the microalgae can sequestrate it. Factors that play a part in this include temperature and light. The pool size will mean that in most of the situations the air temperature will be the temperature of the pool and the heat of the flue gas will change to the air temperature very quickly due to this. Also, light is another factor that effects the rate the microalgae sequestrates the CO_2. This is more important than the temperature due to daylight and nightlight meaning extreme change every day. The 80% CO_2 sequestered in the references is assumed to factor these in as otherwise it would be expected to be 95-99% considering the huge RWP sizes mentioned.

Most of the literature was focused on cultivating microalgae and a 1191m^2 was investigated linked to a 500MW coal power plant. Not only is this reference considering a larger installed capacity but also a much smaller RWP. The microalgae would need to be harvested almost every day but also a lot of CO_2 would not be sequestered. Temperature and light, but also other factors, i.e. PH, will have more effect on the results. This was important for the point of that project and closer review on fine details could be achieved. For the huge RWPs that are being used in this analysis it is assumed that their huge sizes take into consideration that the microalgae would not need to be harvested for long periods of time as the focus is on carbon sequestered.

To summarise, the maximum percentage of carbon that can be sequestered by RWPs is assumed to be 80%, all factors considered. The 80% will be used a constant for all FFPPs around the world. There is naturally uncertainty with this value, but it is accepted as the average and a constant for the world. The RWPs depth will always be slightly over 1m so that each 1m^3 of volume, that can hold 1 tonne of microalgae, can be recognised for when harvesting of the microalgae would be required. Exactly 1 tonne of microalgae does not necessarily fit to 1m^3 but it is assumed that the extra depth covers the uncertainty of the weight. Microalgae is a very light biomass anyway. Lastly, 1.83 tonnes of CO_2 is needed to produce 1 tonne of microalgae.

Reconsidering the two references, the amount of carbon produced per day can now be applied to figure out the amount of microalgae that would be produced daily by each.

The gas power plant produced 1,170.6 tonnes of CO_2 per day to which 936.5 tonnes of CO_2 were sequestered.

$$\frac{936.48}{1.83} = 511.74 Tonnes/Day$$

511.74Tonnes of microalgae would be produced per day at this rate. The depth of the RWP was over 1m allowing space at the bottom so that the RWP was not just completely microalgae sludge but still a solution with water. This means that if the RWP was multiplied by a depth of 1m, making the maximum space that microalgae can be held in that the volume of the pond that can hold microalgae can be stated as 14,569,000m^3 or the RWP can hold 14,569,000Tonnes of microalgae in total. The actual depth is larger than 1m.

$$\frac{14{,}569{,}000}{511.74} = 28{,}468 Days$$

It would take around 28,000 days for a RWP this size for the microalgae to require harvested. This is over 75Years. The same calculation for the RWP at the coal power plant gives:

$$\frac{28{,}328{,}000}{(2179.44 \div 1.83)} \div 365 = 65 Years$$

It can be assumed that the RWP sizes, for carbon sequestration, were decided where the microalgae would never have to be harvested. The number of years calculated for each power plant would even outlast that of the life of a modern FFPP. The depth of these ponds is not stated in the reference and the depth could have been, for example half, of what was was used for the calculation. If it was then the years calculated would have been more realistic for the life of a power plant. The simplifications made for the analysis could have affected these numbers slightly.

The RWPs in the reference were the size of a small town and would not be feasible at all. Decreasing the size of the pond and incorporating harvesting the microalgae, maybe a few times, in its life would be much more feasible. There are many FFPPs that will be closing within a decade or two and will be replaced with low carbon technologies. Both of these aspects are taken into account for the analysis of all FFPPs.

There will be slight trial and error when defining the installed capacity categories but using the 200MW references and varying the number of years to produce different sized RWPs will help to visualise what sort of sized RWPs are going to be required throughout.

The coal power plant reference will be investigated first to calculate the size of RWP required if microalgae was harvested ever 6 years, 2 years, 1 year and 6 months.

$$\frac{2179.44}{1.83} \times 365 \times 6 = 2{,}608{,}182 m^2$$

$$\frac{2179.44}{1.83} \times 365 \times 2 = 869{,}394 m^2$$

$$\frac{2179.44}{1.83} \times 365 \times 1 = 434{,}697 m^2$$

$$\frac{2179.44}{1.83} \times 365 \times 0.5 = 217{,}349 m^2$$

As there is only one variable the results are linear, but it is valuable to visualise them to help narrow the categories. Each category will have one size of RWP for all the power plants that fall into the category.

The first power plant type that will be dealt with is the coal power plants.

The smallest installed capacity coal power plant is 1.2MW. This will produce:

$$\frac{1.2 \times 0.567 \times 24 \times 1{,}001}{1{,}000} = 16.35 TonnesCO_2/Day$$

Or 5967.75TonnesCO_2/Year.

The highest achievable CO_2 sequestrated would therefore be:

$$5967.75 \times 80\% = 4774.2 TonnesCO_2/Year$$

The RWP size that would be able to sequestrate this amount of CO_2 and only require the microalgae to be harvested once a year would be:

$$\frac{4774.2}{1.83} = 2609 m^2$$

This size of this RWP is pretty large for such a small power plant but if it was to be used for all power plants up to a certain capacity where these other power plants just harvest the microalgae more often it would be considered a very reasonable figure. Sticking to small installed capacities, 30MW can be investigated. This would cover 129 coal power plants. Firstly, a 30MW plant where harvesting occurs once a year will be considered to see the difference in size between the smallest and largest installed capacities for what could be the first category. Due to the linear progression the RWP size calculated before would simply be multiplied by 25 to calculate this. A RWP of 65,225m^2 would therefore be needed. A 65,225m^2 RWP would not be able to next to every small-scale power plant but it is not really an unrealistic size (about 50 Olympic swimming pools) for these RWPs but it would not be found outside these small power plants. This means that harvesting will need to be completed more often to factor in realistic sized ponds.

The first category can cover 0-30MW fairly and based on the sizes found for 200MW anything above that will need to be treated as one category as the RWPs are so vast already. Going from this, four categories can easily be found:

- 0-30MW Installed Capacity
- 30-100MW Installed Capacity
- 100-200MW Installed Capacity
- 200+ MW Installed Capacity

These categories will be applied for oil and gas power plants also.

Coal was always going to push the boundaries of realism with the RWP sizes due to the carbon emissions associated with coal. Keeping the maximum 80% carbon sequestration and realistic RWP sizes will prove difficult in the 200+ MW category where most of the emissions associated with the worldwide power plants will occur. Harvesting the microalgae much more often will become necessary to have realistic RWPs next to these 200+ MW power plants. One key point with this is that the other technologies are already requiring daily storage/use of the CO_2 sequestrated so even once a week would be more efficient than this. Unfortunately, once the microalgae would be removed whatever it is used for will produce carbon emissions even if it was burying it. Table 8 shows what is most important within this project.

	Size of RWP	CO_2 Sequestered	Rate of Harvesting
Importance to the Project (High/Medium/Low)	Medium/High	High	Medium/Low*

Table 8 – Project Properties

*If the rate of harvesting is less than once a day

The 80% carbon sequestration will therefore aim to be theoretically achieved allowing for slightly unrealistic RWP sizes. The harvesting would most preferably be once in the lifetime of the power plant but that is just not feasible. Minimum of once a week microalgae harvesting will be included to ensure the carbon sequestration and RWP size takes priority.

Figure 22 shows the percentage split of the number of coal power plants in each category and Figure 23 shows the spread of total installed capacity from each category.

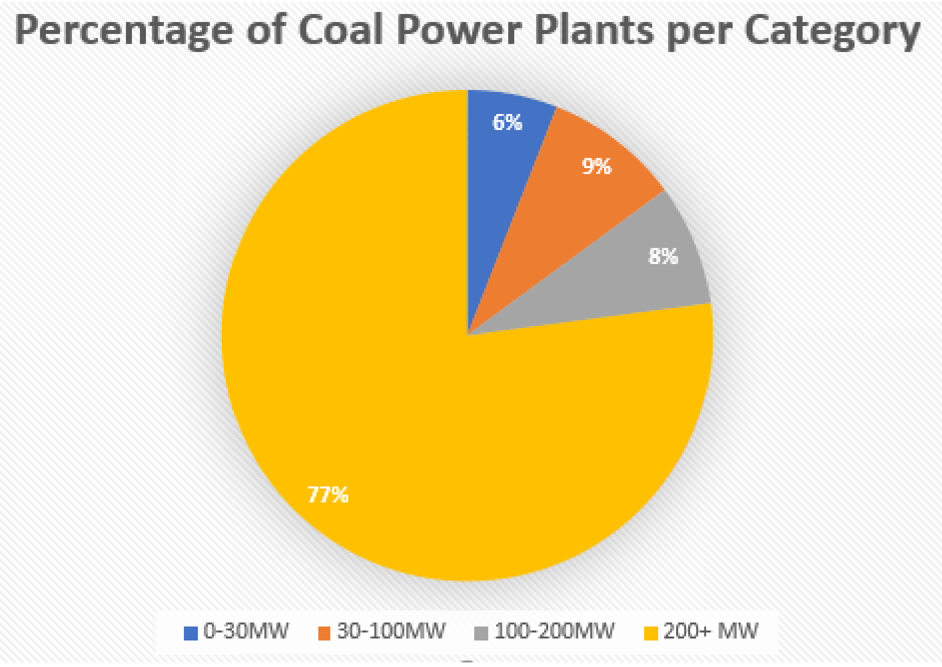

Figure 22 – Percentage of Coal Power Plants per Category

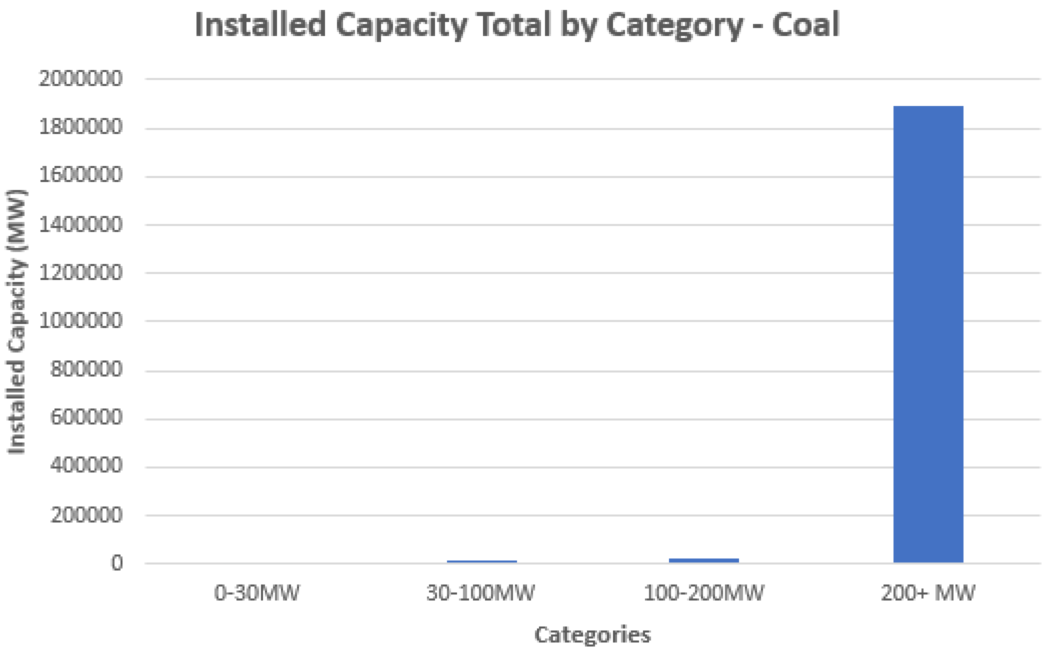

Figure 23 – Installed Capacity Total by Category – Coal

The installed capacity in the 200+ MW category is by far the majority of the total installed capacity from all coal power plants. Figure 22 does not particularly correlate with Figure 23 as the three other categories do not even combine to 10% of the total installed capacity. It is assumed this will be the same for the oil and gas power plants. Figure 24 shows the split for oil power plants and Figure 25 shows the split for gas power plants.

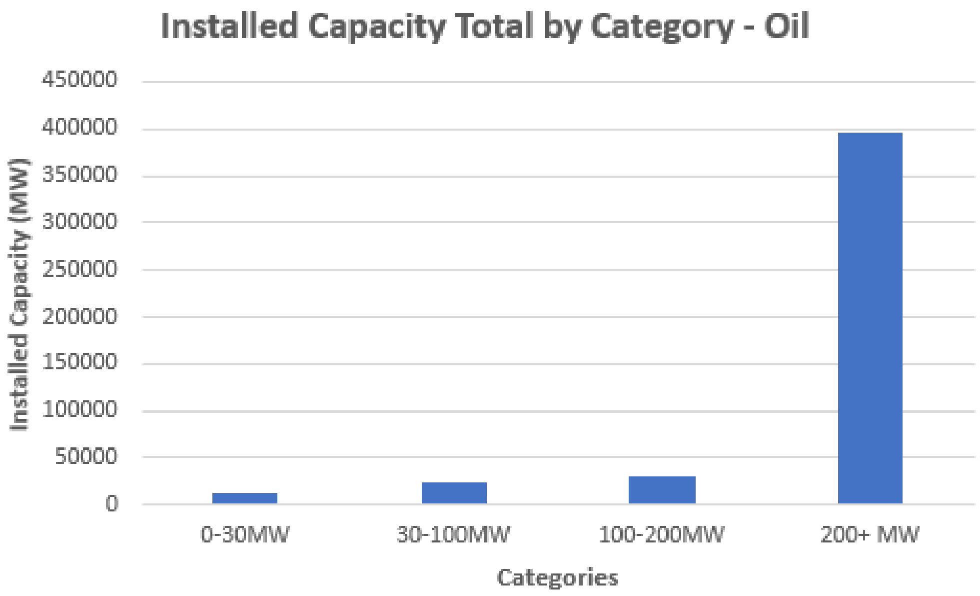

Figure 24 – Installed Capacity Total by Category - Oil

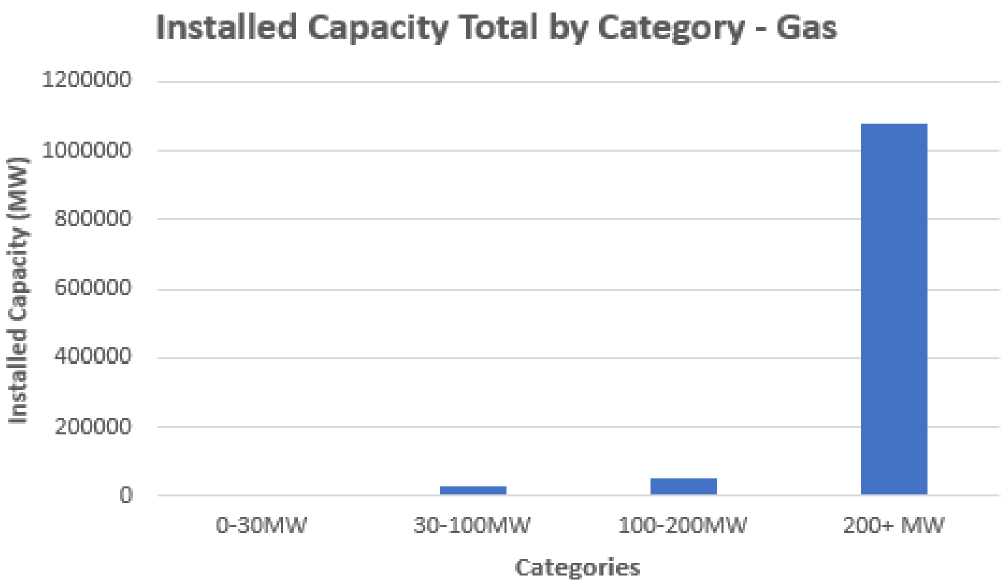

Figure 25 – Installed Capacity Total by Category - Gas

The pattern does continue for the categories into the oil and gas power plants. The three graphs show that when considering global carbon emissions that the 200+ MW category requires by far the most attention. The other three categories can have varying realistic RWP sizes throughout but on a global scale the carbon emissions sequestered are minimal compared to the 200+ MW category and near enough negligible in terms of overall global carbon emissions.

The RWP sizes for all categories for each fuel will be now be found.

The 0-30MW category in the coal powered plants has already been considered and a 65,225m^2 RWP was found for the top end of this category where harvesting was required once a year. Due to the liner manner of the calculations this means that the smallest RWP in this category would only require the microalgae to be harvested once every 25 years. At roughly 10 Olympic sized swimming pools, a 13,045m^2 would fulfil this category, where the top end of the category would require microalgae harvesting once every two and a half months and the bottom end once every 5 years.

The top end of the 30-100MW will require harvesting more often than the 2 and a half months to ensure the RWP size has some realism. If the harvesting was completed once every 1 and a half months, then the RWP size would be:

$$\frac{100 \times 0.567 \times 24 \times 1{,}001 \times 365 \times 0.8}{1{,}000} \div 1.83 \times 0.125 = 27{,}168m^2$$

At roughly 272 Olympic swimming pools, this would still be reasonably achievable for this category, but these are still very small power plants so would be difficult to consider this completely feasible.

At the top end of the 100-200MW category, it has already been found that for a 200MW coal power plant where harvesting is completed twice a year a RWP of 217,349m^2. If the harvesting was reduced to once a month then a RWP of 36,224m^2 would be used for this category. This is roughly 29 Olympic swimming pools in size. It is larger than the RWP for the 30-100MW category and the harvesting is required at a faster rate. It would also be difficult to consider this size of RWP feasible considering the little carbon emissions that are being sequestrated on a global scale.

The last category is the 200+ MW category and the RWP will be extremely large in this category. At the top end of this category, where the microalgae with the microalgae harvested once a week a RWP of size:

$$\frac{5500 \times 0.567 \times 24 \times 1{,}001 \times 365 \times 0.8}{1{,}000} \div 1.83 \times 0.019 = 227{,}131m^2$$

The lower end of this category would require the microalgae to be harvested roughly once every 6months. At 227,131m^2 this is roughly 182 Olympic sized swimming pools. In the largest power plants this size of RWP could be accommodated but realistically there would only be select power plants that could accommodate this.

Figure 26 helps visualise how the RWP size per highest installed capacity per category contrasts with the number of days harvesting is needed.

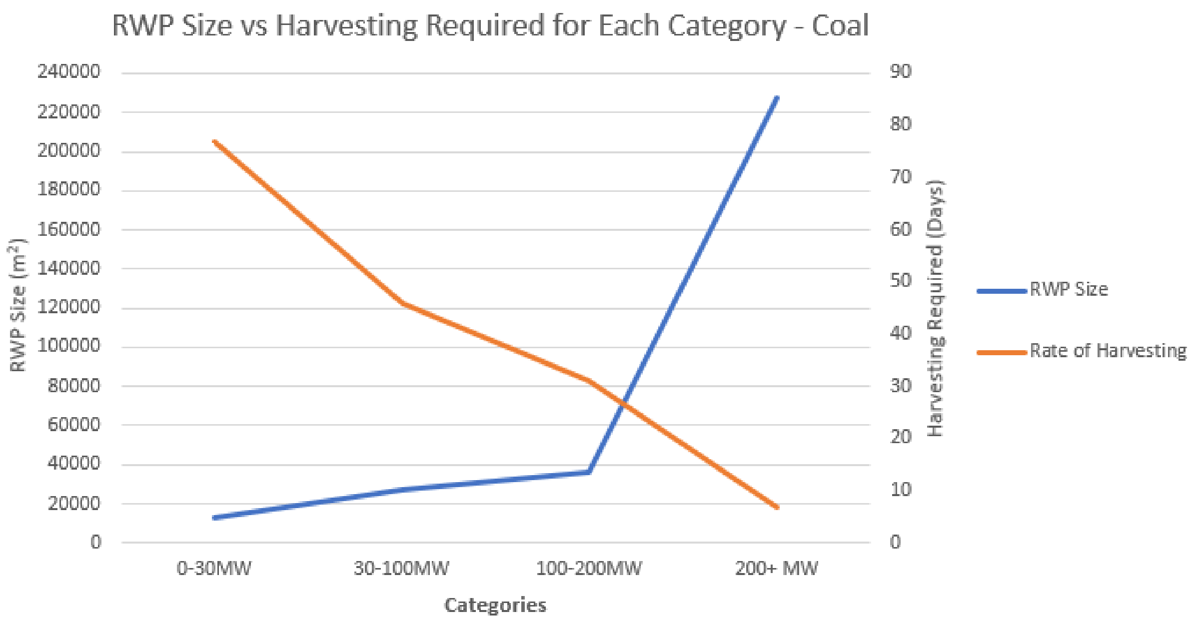

Figure 26 – RWP Size vs Harvesting Required for Each Category - Coal

Although the RWPs, especially within the 200+ MW category, are pushing the boundaries of realism and feasibility, the carbon emissions sequestrated are 80% of the total associated with coal power plants. If this can be achieved for coal power plants, then oil and gas can also achieve this as they have lower emission rates than coal.

The same number of days for harvesting will be kept so the RWP size difference for oil and then gas can be found and graphed in the same form as Figure 26.

Starting with oil power plants first, the next 4 equations below, in order of each category will calculate the RWP size.

$$\frac{30 \times 0.5 \times 24 \times 840 \times 365 \times 0.8}{1{,}000} \div 1.83 \times 0.21 = 10{,}133m^2$$

$$\frac{100 \times 0.5 \times 24 \times 840 \times 365 \times 0.8}{1{,}000} \div 1.83 \times 0.125 = 20{,}105m^2$$

$$\frac{200 \times 0.5 \times 24 \times 840 \times 365 \times 0.8}{1{,}000} \div 1.83 \times 0.083 = 26{,}699m^2$$

$$\frac{6794 \times 0.5 \times 24 \times 840 \times 365 \times 0.8}{1{,}000} \div 1.83 \times 0.019 = 207{,}621m^2$$

For gas power plants, the next 4 equations below, in order of each category will calculate the RWP size that would be required.

$$\frac{30 \times 0.52 \times 24 \times 469 \times 365 \times 0.8}{1{,}000} \div 1.83 \times 0.21 = 5{,}884m^2$$

$$\frac{100 \times 0.52 \times 24 \times 469 \times 365 \times 0.8}{1{,}000} \div 1.83 \times 0.125 = 11{,}674m^2$$

$$\frac{200 \times 0.52 \times 24 \times 469 \times 365 \times 0.8}{1{,}000} \div 1.83 \times 0.083 = 15{,}503m^2$$

$$\frac{8868 \times 0.52 \times 24 \times 469 \times 365 \times 0.8}{1{,}000} \div 1.83 \times 0.019 = 157{,}361m^2$$

Figure 27 and Figure 28 have the same style of graph as Figure 26. Figure 27 is for oil power plants and Figure 28 is for gas power plants. These are shown below.

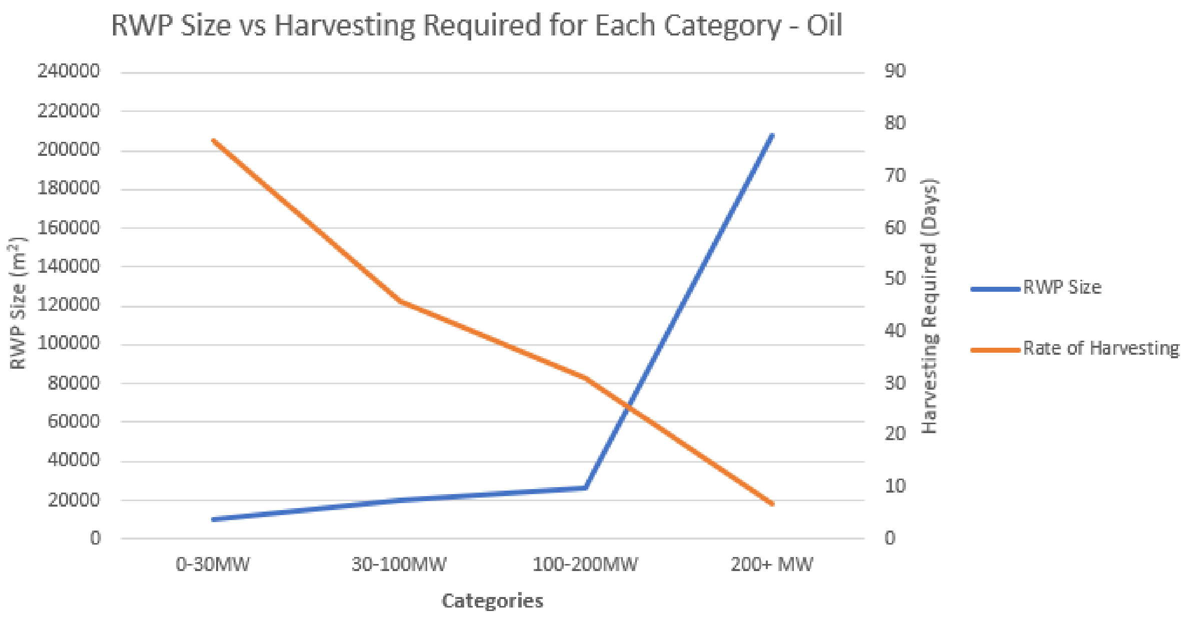

Figure 27 – RWP Size vs Harvesting Required for Each Category - Oil

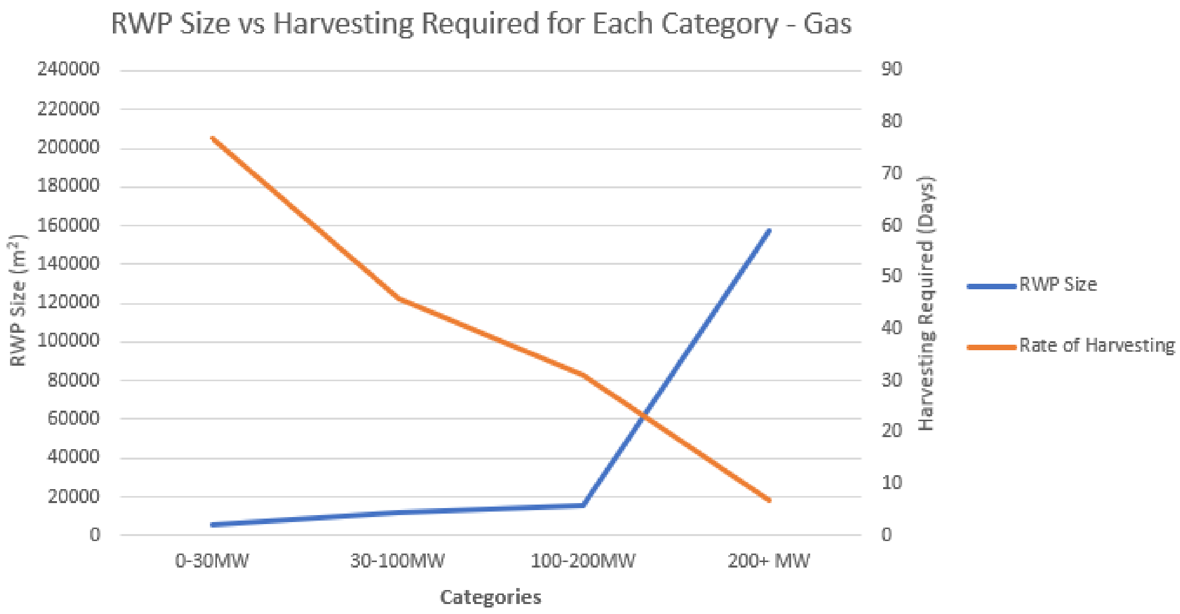

Figure 28 – RWP Size vs Harvesting Required for Each Category - Gas

For the coal and oil graphs in Figure 26 and 27 respectively, the point where the lines cross is around a RWP size of 70,000m^2. This same point for gas is closer to 60,000m^2 as seen in Figure 28. The blue line before this point have acceptable rates of harvesting the microalgae considering the RWP size and after this point the need for harvesting is too great for the RWP size. This falls somewhere beyond power plants with 200MW and below 1000MW of installed capacity. As the size of the RWP was of medium/high importance, which was shown in Table 8, the sizes always needed to have a certain degree of realistic potential but most importantly reach the 80% of CO_2 sequestered.

The RWPs that have been selected/calculated have the potential to sequester 80% of carbon emissions produced by FFPPs but this is not technically true as the harvesting of the microalgae would reproduce some carbon emissions no matter what it was used for. So simply taking 80% of the 14.17Gt (carbon emissions per year by all FFPPs) is not accurate. It is not possible to put a value on this unless the carbon sequestration was for extreme short-term use, i.e. months even days. This is still more efficient than the other technologies where the carbon sequestrated are reproducing emissions daily. On the other hand, these technologies are not requiring kilometres upon kilometres of land to be utilised. As the harvesting rate was more often than preferred, completing a sensitivity analysis for decreasing the RWP sizes is of no value. The harvest rate would increase when lowering the size of the RWPs.

This analysis has been simplified throughout with numerous assumptions. The results provide a global account of the requirements that would be needed to use microalgae RWPs as a carbon sequestration technology linked to FFPPs. The priority table (Table 8) directed the calculations completed. This was specific to this project and prioritising is subjective, so similar work could provide varied answers.

Some of the results are slightly unrealistic, for example a 1MW oil power plant, which is probably a diesel generator that could be found in a barn, would not have a 10,133m^2 RWP next to it, where the microalgae is only harvested after 6 years. The amount of CO_2 sequestered in this time is negligible globally. This type of RWP would be more valuable for sequestrating CO_2 from the atmosphere. Although it is not realistic, the categories needed to be created to simplify the analysis and help to produce the global image for this microalgae technology.

It is clear through the analysis that using a microalgae RWP as a carbon sequestration technology would work most effectively in a selective process where specific power plants could utilise it. Using other carbon sequestration technologies for other power plants would be the most efficient way of using microalgae RWPs in this manner.

This projects focus is fully on the carbon sequestration aspect but what is done with the harvested microalgae would apply a twist to the results gained in this project. Using the microalgae adds more value to the technology and most of the literature found was focused on the value of the microalgae and harvesting it for its numerous uses. The carbon sequestration property of microalgae is one of its weaker traits, so it shows how versatile it can be.

4.3 ECONOMICS ANALYSIS

This section is a basic economic analysis focusing on the capital costs associated with the microalgae RWPs found in the carbon sequestration calculations but also how this compares to other carbon sequestration technologies. Table 9 shows the capital costs found for each sequestration technology from the literature.

Technology	Capital Cost per m^2	Capital Cost per Tonne of CO_2 Sequestrated
Microalgae RWP	£11.33	
Microalgae PBR	£120.56	
Ammonia Scrubbing		£42.37
Amine Scrubbing		£28.35
Land Cost	£2.78	

Table 9 – Capital Costs of Sequestration Technologies

The capital costs in Table 9 for all technologies cover everything that would be required to start the carbon sequestration process. The costs per Tonne of CO_2 sequestrated does not take into account the losses when the CO_2 is stored deep in geological formations for example. It considers just the CO_2 that is captured within the exhaust pipe of a power plant.

Firstly, the total costs for the microalgae RWPs selected for the carbon sequestration calculations. Table 10 and Table 11 capture the data needed to calculate the economics associated with the RWPs for each category and each fossil fuel type.

Fossil Fuel Type	0-30MW, RWP Size (m^2)	30-100MW, RWP Size (m^2)	100-200MW, RWP Size (m^2)	200+ MW, RWP Size (m^2)
Coal	13,045	27,168	36,244	227,131
Oil	10,133	20,105	26,699	207,621
Gas	5,844	11,674	15,503	157,361

Table 10 – RWP Size per Category – All Power Plants

Fossil Fuel Type	0-30MW, Number of Plants	30-100MW, Number of Plants	100-200MW, Number of Plants	200+ MW, Number of Plants
Coal	129	193	173	1670
Oil	1753	414	214	482
Gas	660	512	373	1398

Table 11 – Number of Plants per Category- All Power Plants

The coal power plants will be considered first. The calculations below accumulate to the total capital cost of all microalgae RWPs implemented for coal power plants globally. These calculations follow from the carbon sequestration results that were analysed.

$$(11.33 + 2.78) \times 13{,}045 \times 129 = £23{,}744{,}379$$

$$14.11 \times 27{,}168 \times 193 = £73{,}984{,}713$$

$$14.11 \times 36{,}244 \times 173 = £88{,}472{,}691$$

$$14.11 \times 227{,}131 \times 1{,}670 = £5{,}352{,}046{,}745$$

Total capital cost to implement microalgae RWPs for coal power plants = £5,538,248,528

Around 97% of the costs comes from the coal power plants that are in the 200+ MW category.

The costs associated with the oil power plants are accumulated below.

$$14.11 \times 10{,}133 \times 1{,}753 = £250{,}638{,}032$$

$$14.11 \times 20{,}105 \times 414 = £117{,}444{,}162$$

$$14.11 \times 26{,}699 \times 214 = £80{,}618{,}698$$

$$14.11 \times 207{,}621 \times 482 = £1{,}412{,}034{,}573$$

Total capital cost to implement microalgae RWPs for oil power plants = £1,860,735,465

Around 76% of the costs are from the 200+ MW category for the oil power plants.

The costs associated with the gas power plants are accumulated below.

$$14.11 \times 5{,}844 \times 660 = £54{,}422{,}834$$

$$14.11 \times 11{,}674 \times 512 = £84{,}336{,}712$$

$$14.11 \times 15{,}503 \times 373 = £81{,}592{,}754$$

$$14.11 \times 157{,}361 \times 1398 = £3{,}104{,}068{,}467$$

Total capital cost to implement microalgae RWPs for gas power plants = £3,324,420,767

Around 93% of the costs are from the 200+ MW category for the gas power plants.

Implementing microalgae RWPs for CO_2 sequestration at all FFPPs in the world would cost the global economy:

$$£5{,}538{,}248{,}528 + £1{,}860{,}735{,}465 + £3{,}324{,}420{,}767 = £10{,}723{,}404{,}760$$

Or, roughly £10.72Billion.

Equating this cost into cost per tonne of CO_2 sequestrated due to the harvesting of the microalgae factor. Each installed capacity's RWP has a different cost per tonne of CO_2 sequestrated. The harvesting rates vary from weekly to more than a year due to the categorisation. To give an example, if 6 months was the median for harvesting of microalgae then a cost for each tonne of CO_2 sequestered can be calculated.

The cost per tonne of CO_2 sequestrated excludes CO_2 that is lost to the atmosphere. The total global carbon emissions from power plants was calculated as 14.17GtCO_2/Year. In 6 months 7.0875Gt of CO_2 are being emitted. If 80% of this is captured that would be 5.67Gt of CO_2. The cost per tonne of CO_2 sequestrated for the microalgae RWPs under these circumstances would be:

$$\frac{10.72}{5.67} = £1.89\ per\ Tonne\ of\ CO_2\ Sequestrated$$

If the harvesting rate was required at once every two weeks as an average, then the economics associated are:

$$\frac{14.17}{365} \times 14 \times 0.8 = 0.435 GtCO_2$$

$$\frac{10.72}{0.435} = \ £24.64\ per\ Tonne\ of\ CO_2\ Sequestrated$$

The rate of harvesting, at an average of two weeks, is still calculated to be cheaper than the amine scrubbing which is the cheapest of the other sequestration technologies at £28.35per Tonne of CO_2 sequestrated. This is without the amine scrubbing considering the emissions it creates after being stored not long after. It should be noted that the land area cost can differ between land owners and between different countries etc.

The microalgae PBR costs at £120.56 per m^2 does not consider the costs of using other GHG sequestration technologies to ensure that CO_2 is the only GHG that reaches the PBR. This is without adding the land areas costs. The costs associated would be much higher than they already are. PBRs are used for optimising the microalgae growth and properties more than sequestrating CO_2.

Fair comparison with the other technologies on an economical scale proves difficult due to the assumptions/simplifications and categories applied to the microalgae RWPs. There is enough evidence to suggest that the capital costs associated with the microalgae RWPs can be cheaper when considering just the CO_2 sequestered at the power plant. The capital costs to build the microalgae RWP is constant per metre squared required. However, the rate of harvesting is very influential for the cost per tonne of CO_2 sequestrated. The lower the rate of harvesting is beneficial in terms of cost and keeping the 80% CO_2 sequestered for longer. The harvesting process incurs costs also.

The microalgae, once harvested, has so many uses that it can be sold for so if the CO_2 sequestration was of low priority and the economics were of high priority, the sale of the microalgae would be of importance. The microalgae RWPs can have lower capital costs than all other carbon sequestration technologies can also have higher post sequestration sales than other technologies. This further attracts using microalgae and microalgae PBRs, having a more controlled process, would have more valuable microalgae to be sold. The microalgae in RWPs can be contaminated easier than within PBRs so not all the microalgae harvested in RWPs is valuable.

Table 12 gives an overview of the carbon sequestration technologies considered in this project and some of the factors involved with them for comparison.

Technology	**Capital Costs**	**Installation**	**Managing CO_2 Sequestrated**	**Post Sequestration Product Value**
Microalgae RWP	Low	Slow	Monthly	Medium/High
Microalgae PBR	High	Slow	Weekly	High
Ammonia Scrubbing	Medium	Fast	Daily	Low
Amine Scrubbing	Medium/High	Fast	Daily	Low

Table 12 – Carbon Sequestration Technology Comparison

5 CONCLUSIONS

Investigating lowering carbon emissions by using carbon sequestration technologies, at the present, is as valuable as investigating low and zero-carbon energy production technologies. Using carbon sequestration technologies could provide more time to implement low and zero-carbon energy production technologies across the world.

FFPPs, particularly coal power plants are producing huge amounts of carbon emissions and there is accessibility and potential for capturing large amounts of these carbon emissions. Using natural sources to sequestrate these emissions can mean for a cheap technology. Using microalgae, a natural product, to sequestrate CO_2, within a RWP gives this easily implementable technology.

The analysis required many assumptions meaning there is a certain level of uncertainty throughout the results. As the project is considering potential on a global scale these simplifications needed to be made. There will be variations on many details across the world for many of the aspects.

Microalgae RWPs carbon sequestration ability is influenced by so many factors including temperature, light and PH. These factors had to be considered negligible on a global scale but light especially will vary in different areas of the world. Categorising the RWPs by installed capacity of power plants helped to find more average and realistic RWP sizes but basically all 7971 FFPPs would all have their own specific sized RWP. This does not factor that some power plants would not have the space to utilise this size or pond. A broad overview, capturing how large the RWPs would need to be to act as a sole solution in sequestrating carbon emissions from FFPPs is created within the results. The RWP sizes are chosen from investigating the top end of each category. This means they are very large in certain circumstances and can be unrealistic. It is still clear that the technology could not be used solely globally. Investigating a small country or region, analysing the technology, considering all variables and strategising using the microalgae when harvested could be a worthwhile endeavour. The microalgae RWPs become much more valuable when the microalgae harvested is used productively but it creates emissions which was not favourable in this project.

A global strategy for carbon sequestration of all FFPPs would use a mix of technologies and the microalgae RWPs do have a place within this type of strategy especially if the economics were prioritised. RWPs solely for carbon sequestration have the potential to be the cheapest technology in this area but the land space available is the key factor for this to be the case. One distinctive factor for the RWPs was that the flue gas from the power plant does not require separated and can be piped in its original composition to the RWP. This is extremely useful economically.

Microalgae is better known for its bioenergy capabilities, but its versatility has allowed it to be considered in a project that focuses on CO_2 sequestration. Investigating it on a global scale for this was ambitious. Unfortunately, many assumptions had to be made to accommodate this. Focusing on a smaller scale to decrease the number of assumptions, would be recommended in following up this work.

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7 APPENDICES

The full list of power plants is within a downloadable Excel file and is found at (WRI, 2018). This file was manipulated so that just coal, oil and gas power plants were left, and these were placed in different sheets respectively. Instead of having the full tabulated lists that would stretch over 100pages, a sample of each will be shown.

APPENDIX A – TABLE OF GLOBAL COAL POWER PLANTS

Country	Power Plant Name	Installed Capacity (MW)
Denmark	Randers	52
Denmark	Stigsnaesvaerket	264
Denmark	Studstrupvaerket	730
Dominican Republic	Barahona Carbon	45.6
Dominican Republic	Itabo 2	260
Fiji	Levuka Power Station	2.98
Fiji	Wailoa	80
Fiji	Wainikasaou	6
Finland	Hanasaari B	212
Finland	Meri-Pori	565
Finland	Salmisaari B	163
Finland	Vaskiluoto 2	230
France	CORDEMAIS 4	1160
France	EMILE HUCHET	995
France	HAVRE 4	580
France	LUCY 3	245
France	PROVENCE 5	595
Germany	Bergkamen	717
Germany	BoA 2	2100
Germany	Boxberg	2427
Germany	Braunkohlekraftwerk Lippendorf	875
Germany	Buschhaus	352
Germany	Coal Plant #1	17.5
Germany	Coal Plant #2	18.5
Germany	Deuben	67

Table 13 – Coal Power Plants Appendix A

APPENDIX B – TABLE OF GLOBAL OIL POWER PLANTS

Country	Power Plant Name	Installed Capacity (MW)
Pakistan	Saba Power Company Sheikhupura	114
Pakistan	Southern Electric Power Company	135
Pakistan	Tapal Energy Limited Karachi	126
Panama	ACP Miraflores 3 and 4 Thermal Power Plant Panama	59
Panama	ACP Miraflores IC Power Plant Panama	54
Panama	PanAm IC Power Plant Panama	96
Panama	Pedregal Pacora Power Plant Panama	53.4
Papua New Guinea	Kanudi	24
Papua New Guinea	Lae	30
Papua New Guinea	Ok Tedi	45
Papua New Guinea	Porgera	13
Papua New Guinea	Tabubil	16
Papua New Guinea	Tolkuma	3.5
Papua New Guinea	Ulagunan	8.4
Philippines	BAJADA DPP	58.7
Philippines	BAUANG DPP	235.2
Philippines	CALIBU DPP	30
Philippines	CEBU DPP (Salcon)	43.4
Philippines	COTABATO LIGHT	10
Philippines	Calumangan DPP	23
Philippines	GUIMARAS POWER	3.4
Philippines	LIMAY CCGT	620
Philippines	MALAYA	650
Philippines	NAC DPP	10.9
Philippines	PACERM-1	10.5
Philippines	PB 101	32
Philippines	PB 104	32
Philippines	PETERSVILLE DPP	9
Philippines	SPPC	59
Philippines	SUBIC DPP	116
Philippines	WMPC	113
Poland	PKN Orlen	345
Rwanda	Jabana 1	7.8
Rwanda	Jabana 2	20
Saudi Arabia	AL WAJH	263.4
Saudi Arabia	AL-JOUF	348

Table 14 – Oil Power Plants Appendix B

APPENDIX C – TABLE OF GLOBAL GAS POWER PLANTS

Country	Power Plant Name	Installed Capacity (MW)
Egypt	Shoubra El-Kheima	1295
Egypt	Sidi Krir	2092
Egypt	Suez Gulf	683
Egypt	Talkha	1460
Egypt	Wadi Hof	100
Equatorial Guinea	Bioco Lpg Plant	10.5
Equatorial Guinea	Malabo	20
Estonia	IRU Elektrijaam	173
Estonia	Kiisa AREJ 2	250
Fiji	Levuka Power Station	2.98
Fiji	Wailoa	80
Fiji	Wainikasaou	6
Finland	Haapavesi	2.7
Finland	Ikaalinen	6
Finland	Joensuu	68
Finland	Kerava	3.7
Finland	Kirkniemi	128
Finland	Koneharju kt	4.6
Finland	Lappeenranta kombi	26.3
Finland	Lielahti	142
Finland	Martinlaakso	171.7
Finland	Myllykoski vp	32.8
Finland	Naantali G1 2 ja 3	290
Finland	Naistenlahti 2	191.2
Finland	Nokia kombi	72
Finland	Porvoo kt 2	120.6
Finland	Tako T2 ja T5	16.5
Finland	Vuosaari A	163
Finland	Vuosaari B	485
France	BLENOD 5	427
France	BOUCHAIN 7	575
France	COMBIGOLFE	425
France	Croix-de-Metz	413
France	DK6	796
France	EMILE HUCHET	826
France	GENNEVILLIERS 1	203
France	MARTIGUES PONTEAU	930
France	Pont-sur-Sambre	412

Table 15 – Gas Power Plants Appendix C