Tampere University of Applied Sciences

Economic Feasibility of Microalgae as a Biological Carbon Capture Solution

Financial Comparison with Traditional Chemical Carbon Capture Technologies

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ABSTRACT

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Despite the growing affordability of renewable energy, fossil fuels remain the largest source of global power supply, providing two-thirds of the world's electricity. This is especially true in developing countries that lack the infrastructure for large-scale adoption of renewable technologies. This highlights the crucial role of carbon capture in mitigating the effect of greenhouse gases on the environment, while non-renewable energy sources remain dominant.

This thesis evaluated the economic viability of microalgae as a biological method for carbon capture by drawing comparisons with chemical technologies used today.

The study conducted a comprehensive analysis of literature reviews, simulations, small-scale pilot tests, and real-life projects to thoroughly examine the costs per tonne of CO_2 captured using chemical capture technologies and microalgae. Chemical methods were categorized based on their CO_2 source: either from effluent gas or directly from the atmosphere. For each category, notable real-life projects were examined, including the Quest project in Alberta, Canada, and the Orca plant in Iceland.

The findings indicated that the cost of capturing CO2 from effluent gas typically ranges from $40 to $80 per tonne, whereas costs for atmospheric capture are higher, ranging from $100 to $300 per tonne, however, real-life projects for both methods have higher costs, closer to $100 and $1000 respectively. For Microalgae, secondary sources suggest that the costs per tonne for microalgae capture are significantly higher than those for chemical methods, ranging from $800 to $1600, and even under the most favourable conditions are not expected to drop below $225.

The adoption of microalgae as a biological capture method is highly dependent on the market value of the biomass produced, which could help offset the high capital and capture costs. In its current stage, however, microalgae cannot financially compete with chemical carbon capture technologies.

Key words: chemical carbon capture, biological capture method, microalgae, economic viability, effluent gas

CONTENTS

ABBREVIATIONS AND TERMS

TAMK	Tampere University of Applied Sciences
cr	credit
CCS	Carbon Capture and Storage
CO2	Carbon Dioxide
DAC	Direct Air Capture
EOR	Enhanced Oil Recovery
PBRs	Photobioreactors
Mt	Megatonne (1 million tonnes)

1 INTRODUCTION

Carbon capture and storage (CCS) is a technology aimed at reducing greenhouse gas emissions, contributing significantly to the mitigation of climate change. It involves capturing carbon dioxide (CO2) emissions produced from the burning of fossil fuels in electricity generation or industrial processes and factories, preventing CO2 from entering the atmosphere. The captured CO2 is then transported and stored in geological formations deep underground or sold to industries where the CO2 can be re-purposed. (Metz et al., 2005)

Historically, CCS has been a controversial technology, primarily due to concerns about its effectiveness, costs, and public perception. Initially, there was significant scepticism regarding its potential as a viable solution for mitigating climate change impacts. This scepticism was fueled by uncertainties surrounding the technology's long-term storage security, the risks and environmental impacts of CO2 leakage, and the high energy requirements for CO2 capture and storage processes. Public perception also played a significant role, with low awareness and concerns about the safety of CCS technologies hindering broader acceptance and deployment. (Tcvetkov et al., 2019; Aminu et al., 2017).

However, as research and development in the field have advanced, CCS is beginning to show more promise. Technological advancements and successful pilot projects have demonstrated its potential to significantly reduce CO2 emissions from industrial sources and power generation. The development of more efficient capture technologies, improvements in storage monitoring and safety, and the exploration of utilisation pathways for captured CO2 have contributed to a more optimistic outlook on CCS. This evolving perception of CCS is supported by a growing amount of research and literature that highlights the technical feasibility, environmental benefits, and the crucial role CCS could play in achieving global climate targets. (Seigo et al., 2014; Snæbjörnsdóttir et al., 2020)

Although renewable energy sources are becoming more affordable, coal and gas power plants still produce nearly two-thirds of the world's electricity, a proportion that has not changed significantly since 2000. Since then, the amount of power generated from fossil fuels has surged by 70%, driven by a continuous increase in global electricity demand (IEA, 2020). The continuing dominance of coal and gas in global power generation, coupled with the sector's significant contribution to global CO2 emissions, highlights the essential role of carbon capture technologies, including chemical and biological approaches, in cutting CO2 emissions while ensuring the continuation of energy production.

Chemical and biological carbon capture technologies represent two pivotal approaches in the effort to reduce atmospheric CO_2 levels.

Chemical carbon capture involves the use of solvents or other chemical processes to directly remove CO_2 from industrial or power plant emissions before they are released into the atmosphere. This category includes processes such as post-combustion capture, where CO_2 is absorbed by a solvent after combustion, and oxy-fuel combustion, which burns fuel in pure oxygen to produce a stream of CO_2 and water vapour that is easier to separate. (Metz et al., 2005).

On the other hand, biological carbon capture takes advantage of the natural photosynthetic processes of plants and algae to absorb CO_2 from the air or directly from emission sources. This approach includes a range of strategies, such as the cultivation of microalgae capable of sequestering CO_2. (Falkowski et al., 2000)

The fundamental difference between these approaches lies in their mechanisms of capture. While chemical methods directly interact with emission streams through engineered solutions, biological techniques utilise living organisms to assimilate CO_2 as part of their natural growth processes. This distinction not only affects the efficiency and scalability of each method but also influences their environmental impacts and integration into existing energy systems. (Metz et al., 2005; Smith et al., 2016).

Microalgae cultivation has emerged as a promising biological method for carbon capture, leveraging the natural photosynthetic capabilities of microalgae to absorb CO2 from the atmosphere and industrial emissions. Unlike terrestrial plants, microalgae have higher photosynthetic efficiency and can grow rapidly in various environments, making them highly effective at sequestering carbon (Chisti, 2007). These microorganisms can be cultivated in controlled environments such as photobioreactors or open ponds, where they convert CO2 into biomass, which can then be used for biofuels, animal feed, and other valuable by-products (Wang et al., 2008). The potential for microalgae to capture CO2 directly from flue gases without the need for pre-treatment further enhances their appeal as a sustainable and scalable carbon capture solution (Farrelly et al., 2013). However, while the environmental benefits are well-documented, the economic feasibility of this technology remains a critical factor for its widespread adoption and is the primary focus of this thesis.

The following research questions will dictate this research process:

1. What are the current and projected costs of traditional chemical carbon capture technologies, both from flue gas and directly from the atmosphere?
2. Can microalgae-based carbon capture achieve cost parity with chemical capture technologies in the future?

This Thesis aims to explore the economics of chemical carbon capture technologies and draw comparisons with microalgae cultivation costs to evaluate the financial feasibility of the latter. Selecting the specific chemical capture technologies to be compared is crucial to understand both the well-documented side of carbon capture, as well as more recent and innovative technologies. For this thesis, capture from both effluent gas and directly from the atmosphere will be analyzed.

2 METHODOLOGY

Data collection from literature reviews on existing studies and case studies on carbon capture projects from around the world serve as the foundation for evaluating the economics of conventional capture methods, and whether microalgae can financially compete with these technologies.

The analysis will focus on chemical carbon capture technologies, analysing literature reviews alongside actual data from existing capture plants. This approach allows for a detailed examination of established methods, such as amine-based absorption, calcium looping, and direct air capture. This will provide a grounded comparison point to evaluate microalgae. The financial viability of microalgae cultivation will be assessed through a review of current studies and reports. This dual analysis aims to determine the practicality and economic potential of utilizing microalgae as an alternative carbon capture strategy, comparing it against the established benchmarks of traditional methods.

3 CHEMICAL CARBON CAPTURE

Amine-based carbon capture is a post-combustion capture technology where CO_2 is removed from flue gas through chemical reactions with amine solutions, allowing for the selective capture and subsequent release of CO_2 for storage or use (Rochelle, 2009). Post-combustion carbon capture involves capturing CO_2 from flue gas after the combustion process of the power plant. The flue gas is treated with solvents or other technologies to separate CO_2, which can then be compressed and stored. This method can be applied to existing power plants and industrial facilities. (Cong Chao et al., 2020).

Chemical looping carbon capture is another advanced capture technology that involves a cyclic process using metal oxides to capture CO2 from fossil fuel combustion. An oxygen carrier, typically a metal oxide such as iron oxide or calcium oxide, is alternately oxidized and reduced in separate reactors (Adánez et al., 2012). During the reduction phase, the metal oxide reacts with a fuel, such as coal or natural gas, producing CO2 and water while converting the metal oxide into its reduced form. The reduced metal is then transported to an oxidation reactor where it is re-oxidized with air, releasing pure CO2 and regenerating the metal oxide for reuse. This process allows for efficient separation of CO2 from flue gases without the need for energy-intensive solvent regeneration, making it a promising technology for reducing greenhouse gas emissions from power plants and industrial processes (Czakiert et al., 2022).

Direct Air Capture (DAC) is a capture technology that involves capturing carbon dioxide directly from the atmosphere. This method uses chemical and/or physical filters that react with CO2 in the air to form compounds that can be processed to release concentrated CO2 for storage or utilization (Keith et al., 2018). The air is then released back into the atmosphere, now with lower CO_2 levels. DAC is notable for its flexibility, as it can be deployed independently of emission sources, making it suitable for various geographic locations (US Department of Energy, n.d.).

The primary factors contributing to the costs of traditional chemical carbon capture technologies include capital expenditures for installation, operational expenses, energy consumption, and maintenance costs. The economic viability is also influenced by the market prices of energy and raw materials, regulatory frameworks, and potential revenue streams from carbon credits or by-products (Rochelle, 2009; Keith et al., 2018). Understanding these cost components and their interactions is essential for assessing the long-term sustainability and financial practicality of implementing these technologies at scale.

Financial incentives and regulatory frameworks also play a crucial role in enhancing the adoption and implementation of carbon capture technologies. By reducing the economic barriers and providing financial support, these mechanisms are essential for encouraging industries and energy producers to invest in carbon capture solutions. Policies such as tax credits, subsidies, and grants are designed to offset the high initial costs associated with deploying these technologies and make them more competitive with traditional energy sources. Congressional Research Service, 2020)

One example of such financial incentives is the 45Q tax credit in the United States. This tax credit is specifically aimed at carbon capture, utilization, and storage projects, offering a monetary credit for each ton of carbon dioxide that is captured and sequestered or utilized in various ways. The credit provides up to $50 per ton for CO2 permanently stored in geological formations and $35 per ton for CO2 used in enhanced oil recovery or other end uses (Congressional Research Service, 2020). This substantial financial incentive is designed to lower the cost barrier for companies looking to invest in carbon capture technologies and to stimulate the industry by making projects more economically feasible.

The 45Q tax credit and many other similar incentives have been pivotal for enhancing the economic viability of carbon capture projects. By providing this economic incentive, the government helps to bridge the gap between the operational costs of carbon capture technologies and their financial returns, encouraging more widespread adoption and investment in this crucial climate technology. As industries increasingly focus on reducing their carbon footprints, such financial mechanisms are instrumental in promoting the shift towards more sustainable and environmentally friendly practices. (IEA, 2023)

3.1 Effluent Gas Capture

The Petra Nova Carbon Capture Project, located near Houston, Texas, is one of the largest and most successful examples of amine-based carbon capture technology. This project captures CO2 emissions from a coal-fired power plant by diverting a portion of the flue gas to a separate facility where it is treated with amine solvents. The captured CO2 is then compressed and transported via an 82-mile pipeline to the West Ranch oil field, where it is injected into the underground reservoir for enhanced oil recovery (EOR). The Petra Nova project, which started capturing CO_2 in January 2017, has demonstrated the potential to capture approximately 1.4 million tonnes of CO2 per year, thereby significantly reducing the plant's carbon footprint (DOE, 2021).

The Quest Carbon Capture and Storage (CCS) Project, located in Alberta, Canada, represents another good example in the field of amine-based carbon capture and storage. In the process of turning thick heavy oil (called bitumen) from the oil sands in Alberta into synthetic crude oil, the plant captures approximately 35% of the post-combustion CO_2 of the Scotford Upgrader, which is then transported via a 65km long pipeline. At the 3 well points, the liquid CO_2 is injected more than 2 kilometres underground into the Basal Cambrian Sandstone, a deep saline aquifer, again for EOR. (Open Government Program, 2024). The Quest project has a licensed injection volume of 27 MT of CO_2 and started capturing CO_2 in September 2015, capturing around 1 Mt of CO_2 each year. (Open Government Program, 2024)

The addition of CO_2 into existing oil fields increases the pressure of the reservoir, forcing the oil towards production wells. The CO_2 can also mix with the oil and increase its mobility, allowing for better flow (IEA 2019).

The main cost factors associated with this amine-based technology and chemical carbon capture, in general, include the capital investment required for installation, the energy penalty of running the project, and other operating expenses such as maintaining and repairing the plant if necessary.

The estimated cost of the Petra Nova capture facility is \$65 per tonne of CO_2 captured, compared to the Quest plant, which had a significantly higher average of \$102.5 between 2016 and 2022 (IEA, 2021). A deeper analysis found the cause of this to be the rising operational costs of the Quest plant. The trend is especially noticeable from 2020 onwards, which suggests that operating costs are a significant driver of the overall cost increase. The majority of this cost comes from the purchase and use of energy; power, steam, and cooling water. (Open Government Program, 2024)

It should also be noted that the Petra Nova plant was shut down between May 2020 and September 2023. Taking only the costs of Quest carbon capture before 2020 when Petra Nova was closed, the average cost is $89.3 for the Quest plant.

Based on a techno-eco assessment by Yun et al. of the costs of amine-based carbon capture, the cost per tonne of captured CO_2 was calculated to be $62.8 for the year 2015 (Yun et al, 2022). Several other literature reviews and studies such as techno-eco assessments by Ramezan et al. and Jung & Lee have reported similar results (Ramezan et al. 2007) (Jung & Lee, 2022).

A case study analyzing the commercial feasibility of PacifiCorp's Hunter Plant in the United States evaluated 3 cases with different capture ratios, 48%, 65%, and 90%. The respective cost per tonne of captured CO_2 was found to be $74, $61, and $50 (Panja et al., 2022). Developing the technology further and reducing the usage of water steam and power, the cost can be brought down to $47.1-$50.6/tonne of CO_2 captured (Zheng et al., 2020) (Jiang et al., 2021).

A techno-economic analysis in which a simulated chemical looping capture plant was evaluated found a CO_2 capture cost of $27.5 per tonne. The simulation was done using Aspen Plus (Ogidiama, 2018). Another techno-economic assessment of chemical looping combustion revealed CO2 capture costs of approximately $81 per tonne using synthetic oxygen carriers and $43 per tonne for natural ore carriers, highlighting the significant cost advantage of natural ores over synthetic materials in this technology (Fleiß et al., 2024)

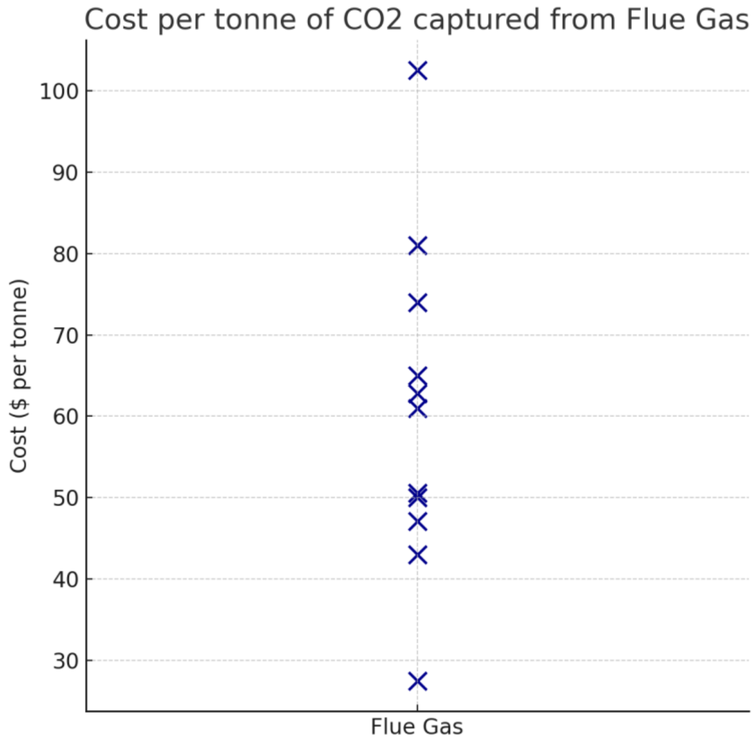

Figure 1. Cost of Capture from Flue Gas

Figure 1 shows the cost per tonne of carbon capture from effluent gas from various literature sources, simulations, and real-life projects. From the graph, it is visible that the average cost per tonne ranges between $40-$80, while keeping in mind that current real-life projects have a slightly higher average, at around $100.

3.2 Direct Air Capture

The current cost estimates for Direct Air Capture (DAC) in literature are quite broad, ranging from \$100 to \$1000 per tonne of CO_2 captured (Realmonte et al., 2019). This wide range reflects the variability in specific technologies, the purity of the CO_2 output, and design differences among DAC systems. Factors such as the scale of deployment, energy sources, and technological maturity also significantly influence the cost, making it challenging to pinpoint a definitive cost for DAC without considering these variables. Another reason DAC is significantly more expensive than other carbon capture methods is due to the dilute concentration of CO_2 in the atmosphere compared to sources like flue gas (IEA 2022). Typically, flue gas contains 8-15% CO_2, whereas the concentration of CO_2 in the atmosphere is only 0.04% (Songolzadeh, 2024).

Climeworks' Orca plant, located in Iceland, is currently the world's largest Direct Air Capture (DAC) facility, designed to capture CO2 directly from the atmosphere. The Orca plant, operational since 2021, captures approximately 4,000 tonnes of CO2 annually (Climeworks, 2021). In 2021, Climeworks co-founder Jan Wurzbacher initially projected reducing the cost of CO2 removal to \$200 to \$300 per ton by the end of the decade, with further declines after that. However, at a summit in June 2023, he updated this estimate, indicating current costs exceed \$1,000 per ton, with anticipated reductions to \$400 to \$700 per ton by the decade's end. The wide cost range is attributed to variable labour, energy, and storage expenses across different locations. Climeworks now aims to lower costs to \$100 to \$300 per ton by 2050, as the technology matures significantly (Pontecorvo, 2024). Climeworks is also exploring the use of renewable energy and waste heat from nearby industrial processes to further cut down operational expenses, enhancing the economic viability of DAC in the long term. (Climeworks, 2021)

Based on a techno-economic assessment by Keith et al., the cost per tonne of captured CO2 using DAC was calculated to be between \$94 and \$232, depending on the technology and operational scale (Keith et al., 2018). The study, which analysed a 1 Mt-CO2/year direct air capture plant, found that smaller-scale operations tend to have higher costs due to lower economies of scale, whereas larger, more optimized plants can achieve the lower end of this cost range. Additionally, the study highlighted that technological advancements and increased operational experience could further reduce costs over time.

Other literature reviews and studies, such as those conducted by Fasihi et al. and Realmonte et al., reported similar results. Fasihi et al. estimated DAC costs to range from $100 to $300 per tonne of CO2, emphasizing the impact of renewable energy prices on overall capture costs, as DAC is highly energy-intensive. The assessment also claimed that prices could reach below $50 per tonne of CO_2 captured by 2040, as the technology becomes more efficient. (Fasihi et al., 2019).

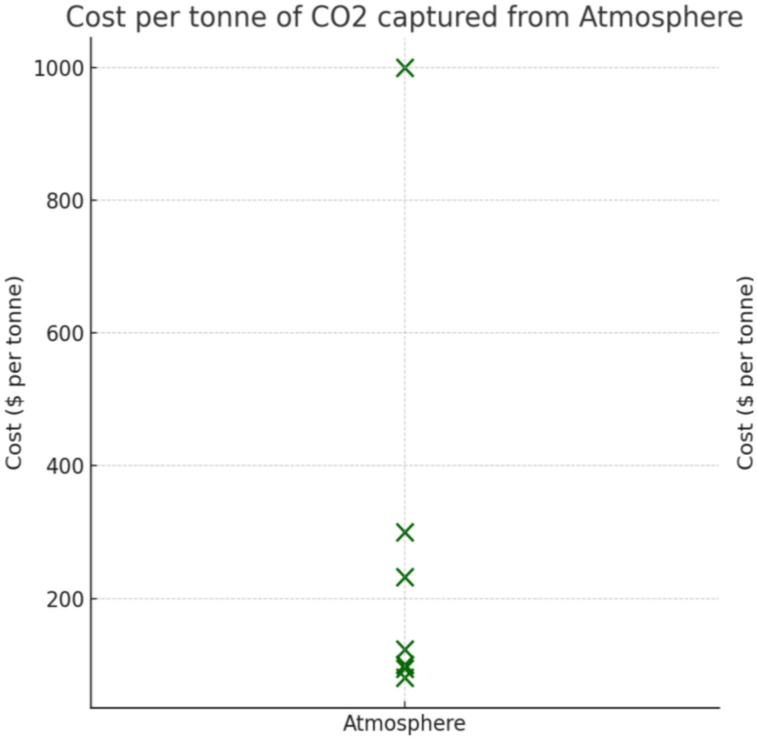

Figure 2. Cost of Capture from the Atmosphere

Figure 2 displays the cost per tonne of capturing carbon directly from the atmosphere. Each point represents a different source, either from literature reviews and studies, simulations, or real-life projects. It is visible from the graph that the average cost per tonne ranges between $100-$300. However, those values are largely from literature, while real-life projects have costs closer to $1000, though they are expected to drop significantly in the next decade or two (Climeworks, 2021).

4 MICROALGAE CULTIVATION

Microalgae are photosynthetic microorganisms that convert CO2 into biomass, thus acting as a carbon sink. Their ability to sequester carbon comes from photosynthesis, where they use light energy to fix CO2 into organic compounds, such as carbohydrates, proteins, and lipids (Zhao & Su, 2020). The efficiency of microalgae in carbon fixation is significantly higher than terrestrial plants, up to 50 times higher, making them a strong tool for atmospheric CO2 reduction (Shukla et al., 2017).

In the context of power generation, microalgae can utilize CO2 from industrial flue gases, offering a direct method for reducing emissions from sources like power plants and factories. The ability of microalgae to grow in high CO2 concentrations, including those present in flue gases, highlights their potential in industrial carbon capture and sequestration applications (Cheah et al., 2015). This dual benefit of treating industrial emissions while producing biomass for biofuels or other bioproducts presents a sustainable model for biological carbon management.

Photobioreactors (PBRs) represent an advanced approach to the cultivation of microalgae, offering controlled environments that optimize growth conditions and enhance photosynthetic efficiency. These closed systems allow for the precise regulation of light, temperature, CO2 supply, and nutrient delivery, factors critical to maximizing microalgae biomass production and CO2 fixation rates (Israel, 2005). Unlike traditional open pond systems, PBRs minimize the risk of contamination and water evaporation, leading to higher biomass yields and more consistent product quality (Carvalho et al., 2006).

4.1 Costs

Microalgae cultivation presents a promising biological approach to carbon capture, making use of the high photosynthetic efficiency of microalgae to absorb CO2 from the atmosphere and industrial emissions. However, the economic feasibility of this method remains a critical factor for its widespread adoption. Current cost estimates for microalgae-based carbon capture are significantly higher than traditional chemical methods, reflecting the early stage of technology development and the complexities involved in cultivation and processing.

The economic viability of this technology is challenged by substantial initial capital costs, particularly those associated with the construction and installation of photobioreactors. These costs are the main contributors to the high expense of microalgae cultivation, which is estimated at $793 per ton of CO2 captured when using open ponds. This cost is excluding additional costs related to the transportation and storage of the resultant biomass (Alabi 2019)., A techo-economic assessment done by Wilson et al. with an amortization period of 10 years estimated that costs can reach up to $1,600 per ton of CO2, which underscores the need for more cost-effective culturing systems that are less expensive to build and install (Wilson et al., 2014).

Even under the most favorable conditions, it is projected that the cost of capturing CO2 with algae will not fall below $225 per ton, while the production of biomass itself costs around $400 per ton. Despite these high costs, there is potential for offsetting expenses through the generation of valuable by-products from the biomass, such as biofuels and high-value chemicals (Wilson et al., 2014) (Alabi, 2009).

Moreover, utilizing flue gases directly for cultivating certain microalgae strains presents an opportunity to bypass the expensive step of CO2 separation. This method leverages the high CO2 concentrations in flue gases for more efficient microalgae growth, eliminating the need for separate CO2 purification processes (Farrelly et al., 2013). However, this direct utilization can subject algae to harsh conditions, potentially inhibiting growth if the gas contains contaminants like sulfur at concentrations as low as 50 ppm (Watanabe & Hall, 1996).

A life cycle and economic analysis by Cole et al. incorporating various scenarios that consider optimistic, baseline, and conservative assumptions, demonstrated carbon removal efficiencies ranging from 73% to 51%, with associated costs of carbon capture and sequestration ranging from $702, $822, to $1,585 per tonne of CO2 sequestered for the three scenarios respectively (Cole et al., 2023). The assessment also suggested that while current costs are high, there is a potential for significant reductions as technologies mature and efficiencies improve.

A case study analyzing the commercial feasibility of microalgae cultivation at a pilot plant in Spain found the cost per tonne of captured CO2 to be approximately $809. This high initial cost was attributed to the growing state of the technology and the small scale of initial plants. However, the study projected that with scaling up and increased efficiency, the costs could be reduced to $232 per tonne (García et al., 2017). The study also mentioned that the use of low-cost renewable energy and integration with wastewater treatment could significantly lower operational costs.

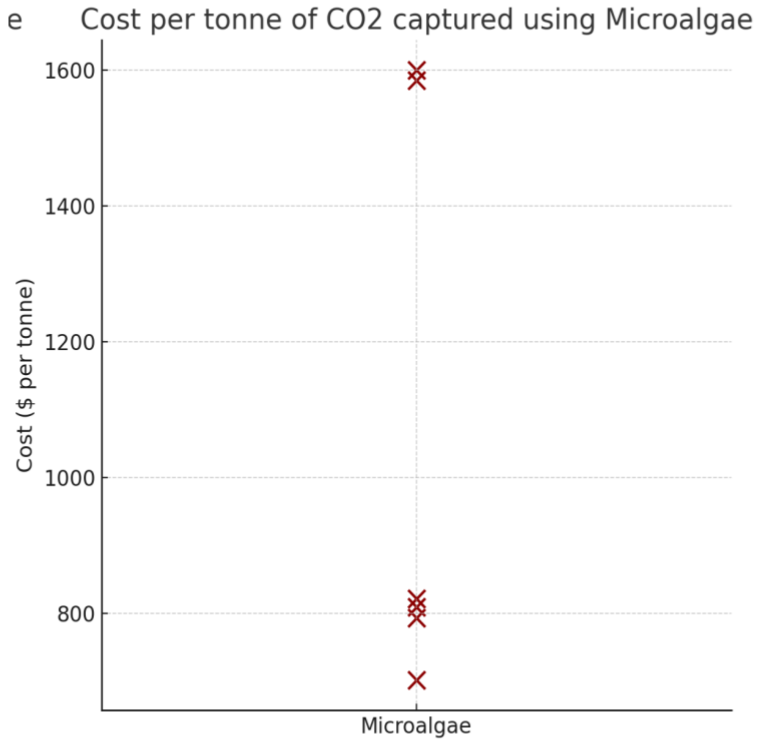

Figure 3. Cost of Capture using Microalgae

Figure 3 helps visualize the cost per tonne of carbon capture while making use of microalgae's capture properties. Data from various literature sources, smaller scale simulations, and test runs allow for a range enough to understand the expected cost if this process is to utilized on a larger scale in the future. From the graph, it is visible that the average cost per tonne ranges between $800-$1600, values much higher than chemical capture technologies.

Despite the potential for lower costs under optimistic conditions, the economic success of microalgae-based carbon capture will ultimately depend on the market value of the biomass produced. In environments where carbon taxes are implemented and fossil fuel prices are high, the economics of producing biomass for biofuels become more favourable, potentially making microalgae cultivation a more attractive solution for CO2 mitigation (Aresta et al., 2005). The financial feasibility of microalgae as a biological carbon capture strategy depends on advances in technology, cost reductions in infrastructure, and the broader economic and regulatory context that can enhance the value of its by-products.

5 COMPARISONS

Assessing the economic feasibility of various carbon capture technologies, it is crucial to consider the financial aspects of each method based on their per-tonne costs of CO2 captured. A comparison between traditional chemical carbon capture technologies and microalgae cultivation reveals significant differences in cost-effectiveness and scalability potential from a financial perspective.

Chemical carbon capture technologies present a range of costs. Flue gas capture technologies are generally more cost-effective, with costs varying from $27.5 to $102.5 per tonne depending on the specific technology and operational scale (Ogidiama, 2018; Open Government Program, 2024). Direct Air Capture operates at a significantly higher cost due to the dilute concentration of CO2 in the atmosphere compared to flue gases. Costs for DAC range broadly from $100 to $1000 per tonne (Realmonte et al., 2019; Keith et al., 2018). Despite these high costs, technological advancements and increased operational scale are expected to reduce costs, with estimates suggesting a potential decrease to around $94 to $232 per tonne (Keith et al., 2018).

Microalgae cultivation, on the other hand, presents the highest costs among the discussed technologies, with estimates ranging from $702 to $1600 per tonne of CO2 captured (Cole et al., 2023). These costs are largely driven by substantial initial capital investments required for setting up photobioreactor infrastructure, alongside the ongoing costs of cultivation and processing. Even in the best case scenario, the cost of capturing CO2 with is not expected to fall below $225 per ton, which is still considerably higher than current chemical carbon capture. (Wilson et al., 2014).

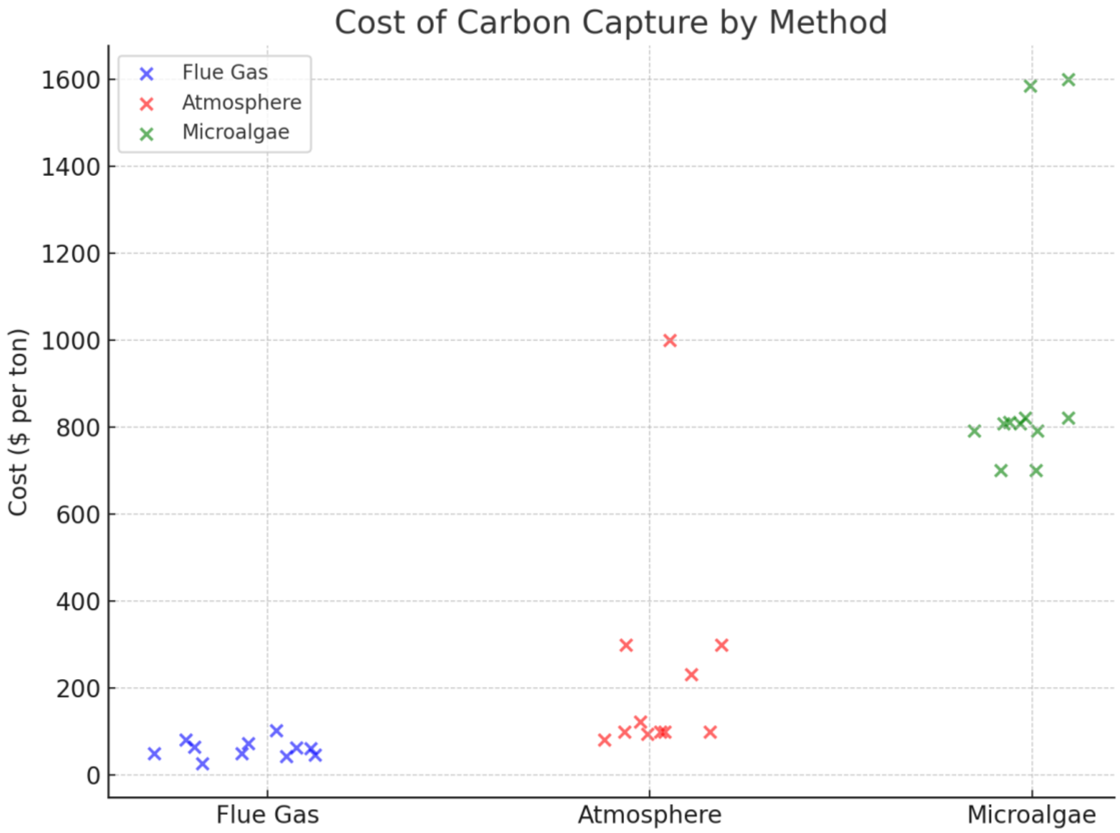

Figure 4. Comparison of Cost of Capture by Method

Figure 4 combines the results of all methods of carbon capture explored in this thesis. Each point represents a different source of data. It is evident from the graph that at its current stage, microalgae can not financially compete with chemical forms of carbon capture, with its cost ranging from 5-20 times higher, depending on the specific technology and source of information.
Comparing these technologies, it is clear that chemical carbon capture methods, particularly those involving flue gas, are currently more economically feasible due to lower operational and capital costs. Microalgae, while being the most expensive option currently, holds potential for cost reductions through technological advancements and operational efficiencies, especially if methods to utilize flue gases directly can be optimized, thus eliminating the need for separate CO2 purification steps (Farrelly et al., 2013).

6 DISCUSSION

In exploring the economic feasibility of microalgae as a biological carbon capture technology, this thesis addresses several critical questions about the current costs, potential for achieving cost parity with traditional methods, and the influence of financial incentives and regulatory frameworks. The financial viability of microalgae cultivation for carbon capture depends on these factors, and through this analysis, insights are made into the economic challenges and opportunities that shape this approach.

The cost of microalgae cultivation for carbon capture is considerably higher than traditional chemical carbon capture methods. This high cost is primarily due to the substantial capital investment required for photobioreactor infrastructure and its installation. Current cost estimates show that capturing CO2 using microalgae in open ponds can be as high as $793 per ton of CO2, which does not account for the transportation and storage of the resultant biomass (Alabi, 2009). Even under the most optimistic scenarios, costs are not expected to fall below $225 per ton, with biomass production itself costing around $400 per ton (Wilson, 2014). However, the potential for generating additional income from valuable by-products derived from biomass could help offset these high costs of mitigation.

Regarding the potential for microalgae to achieve cost parity with traditional chemical capture technologies, the analysis reveals a challenging perspective. Even with advancements in technology and operational efficiencies, the cost of cultivating microalgae remains high. However, the direct utilization of flue gases for cultivating certain strains of microalgae presents a promising avenue to reduce costs by eliminating the expensive CO2 separation step (Farrelly et al., 2013). This method not only lowers the cost of pre-treatment but also harnesses higher CO2 concentrations directly from emission sources, which could enhance the overall economic feasibility of this approach.

Financial incentives and regulatory frameworks significantly impact the adoption of microalgae as a cost-effective carbon capture technology. The 45Q tax credit in the United States is an example of how financial incentives can help bridge the gap between the high initial costs associated with deploying new technologies and their long-term financial benefits. By providing monetary credits for each ton of CO2 captured and sequestered or utilized, such incentives make projects more economically attractive and viable (Congressional Research Service, 2020).

7 CONCLUSION

In conclusion, this thesis has explored the economic feasibility of microalgae as a biological carbon capture solution in comparison with traditional chemical carbon capture technologies. Through extensive financial analysis and comparison, it is evident that while microalgae present an alternate solution for biological carbon capture, the economic barriers currently limit its widespread adoption.

The findings from the thesis suggest that even under the most favourable conditions the cost of capturing CO2 with microalgae is not expected to fall below \$225 per ton, which remains considerably higher than that of chemical methods. For microalgae to become a financially viable option, technological advancements and innovations that reduce overall costs are essential. Supportive regulatory frameworks and financial incentives such as tax credits and subsidies could also play a crucial role in enhancing the economic attractiveness of microalgae-based carbon capture technologies. Finally, the market value of the biomass produced will be a driving factor for the future adoption of this biological capture process.

Future research should focus on the development of more cost-effective cultivation technologies and the integration of microalgae systems with industrial processes to optimize carbon capture efficiencies and reduce costs. Additionally, pilot projects and collaborations with industries could provide practical insights into the scalability and operational challenges of implementing microalgae-based carbon capture on a larger scale.

To improve this thesis, further research could broaden the scope to include more recent and innovative microalgae cultivation technologies and pilot projects. Collecting primary data through collaboration with industries currently deploying these technologies would enhance the accuracy and relevance of the findings. Additionally, long-term studies on the operational efficacy and economic impacts of large-scale implementations would provide deeper insights into the sustainability and practical challenges faced by microalgae-based carbon capture technologies. Including other factors, such as the environmental impacts (land usage, water usage, etc.) could also allow for a more holistic view of the technologies.

Overall, while microalgae in its current stage of development cannot financially compete with chemical carbon capture processes, future research must be done to gain a better and deeper understanding of its potential.

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