Biological Carbon Sequestration: Algae Biomass Farming Part 2

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Abstract

This project explored the conceptual feasibility of carbon sequestration via microalgae for an industrial facility, considering an LNG facility in the North West of Western Australia as a model facility. Evaluating potential solutions to reduce carbon intensity of industrial facilities is of importance in light of State and Federal greenhouse gas requirements. Simulations of a robust algal growth model have been undertaken for both Open Raceway Pond (ORP) and Flat Plate Bioreactor (PBR) configurations, with climate data from a Pilbara coastal location. Results showed that this geography is an optimal location for microalgae growth, through comparison with simulations from Phoenix, Arizona. The ORP growth medium was predicted to produce higher amounts of algal biomass and a higher carbon capture potential than the PBR. A techno-economic analysis was undertaken using technology learning curves to forecast the decrease in price of the system over time. Initial estimates of the total cost of the ORP and PBR systems per kilogram of product were $10.15 AUD and $12.49 AUD. These values were projected to decrease to $8.57 and $9.33 respectively. Recommendations for further work include an in-depth assessment of value-added products to provide profit, validation of the model, and a more robust economic assessment.

1. Introduction

LNG production is a source of carbon emissions associated with the extraction and processing of natural gas. Some of the options for reducing net emissions include process optimization, carbon sequestration, and offsetting.

While considerable effort and resources are allocated to the optimisation of LNG processes to minimise carbon emissions within the oil and gas industry, additional scalable gross emissions reduction approaches to lower carbon intensity of production are of interest. One possible solution is the sequestration of carbon emissions through algal biomass. This technology has significant potential, as it not only directly reduces carbon emissions directly, but value-added products can be created from the biomass such as biofuels, bioplastics, food, and pharmaceuticals. The products could provide an additional source of revenue for the industrial facility, and the decrease in gross emissions could reduce the quantity of offsets required for the facility.

The project objectives have a foundational approach, applying and refining methods used on a previous CEED project by Choong (2023), with potential for further development and refinement in the future. The objectives are as described below:

1. Determine a variety of strains of algae and an appropriate mathematical model to identify a feasible range of algal biomass production.
2. Assess the techno-economic viability through robust analysis, based on the modelled range of biomass production.
3. Evaluate potential uses for algal biomass as a feedstock, as opposed to direct sale of biomass, as a potential for additional revenue.

2. Model Configuration

The model used to characterise the microalgae growth rate in the Pilbara coastal location is a biological model developed by Greene et al. (2021). Past work by Choong (2023) used this model with the in-built Typical Meteorologic Year (TMY3), which is limited to data from given locations within the United States and other international bodies controlled by the USA, such as Guam.

The model code was in the form of an open source MatLab script (Greene, 2024), and was developed for the TMY3 datasets, therefore it was very rigid and wouldn't allow for additional weather data to be easily implemented. To incorporate the Pilbara coast location weather data, the model was translated into Python, which allowed for greater flexibility.

Below outlines how the model calculates the biomass production at each timestep.

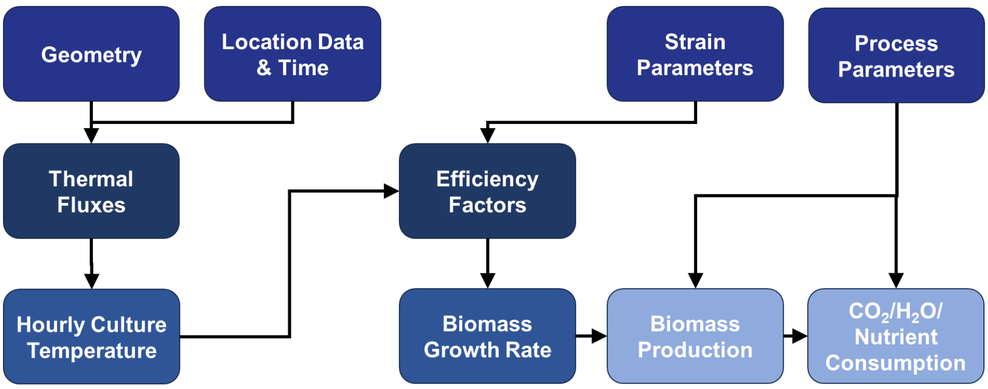

Figure 1 Flowchart of Greene et al. model calculation process. Adapted from Greene et al. (2021).

Efficiency factors dictate the biological growth rate of the microalgal cells in the culture. The Greene et al. model accounts for light, temperature and concentration effects, as well as the decay rate of the culture overnight. These effects are consolidated in the efficiency factors, which form the overall differential equation for the culture growth:

$$\frac{dC_x}{dt} = \frac{\varphi_L(t) * \varphi_T(t) * PAR(t) * \phi_{photon} * A}{V} + \frac{D(t)}{V} \tag{1}$$

Where C_x is the concentration of algal biomass (gm^{-3}), $\varphi_L(t)$ and $\varphi_T(t)$ are the light and temperature efficiencies respectively, and $PAR(t)$ is the total amount of Photosynthetically Active Radiation acting on the culture. A and V are the area and volume of the culture, and ϕ_{photon} is the mass of algal biomass produced in grams per mole of incident light photons. The values followed by '(t)' change with time as calculated at each timestep, whereas the remainder are constant in time. Each component is calculated at each timestep.

$D(t)$ is the decay rate of the algae culture during periods of no sunlight, as photosynthetic growth does not occur at these times. Therefore, the concentration of the culture decreases overnight at this rate, determined by the rate of decay which is specific to the algal strain.

2.1 Summary of Thermal Fluxes

By determining the thermal fluxes at each timestep, the model is able to account for the heat that is gained and lost at each hour, which is dependent upon the geometry of the culture. Two geometries are included into the model, both Open Raceway Pond (ORP) and Flat Plate Bioreactor (PBR), and thermal fluxes accounted for in each geometry are in figures 2 and 3 below.

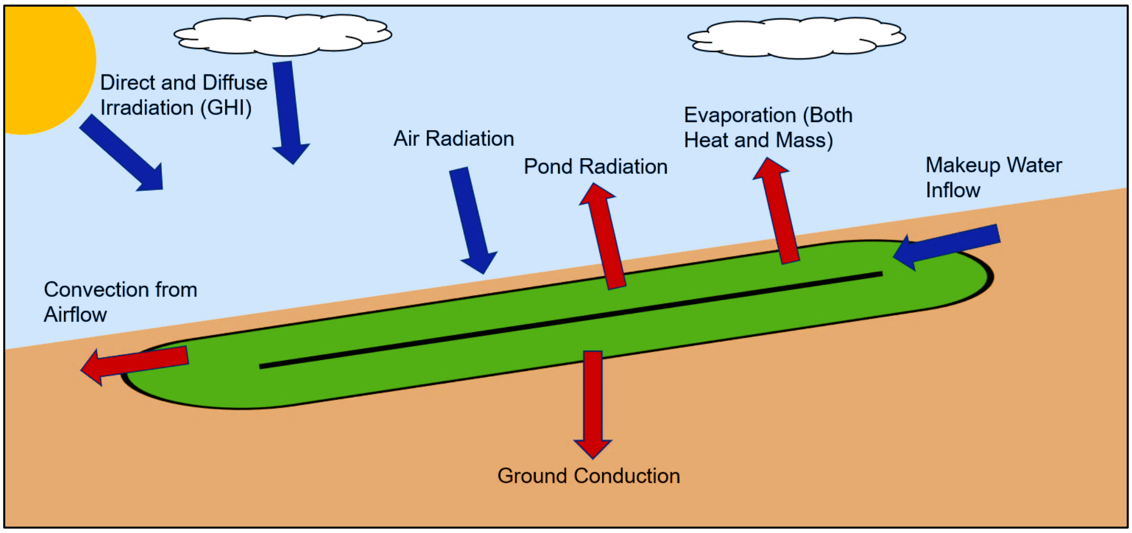

Figure 2 Diagram of heat fluxes for open raceway pond model.

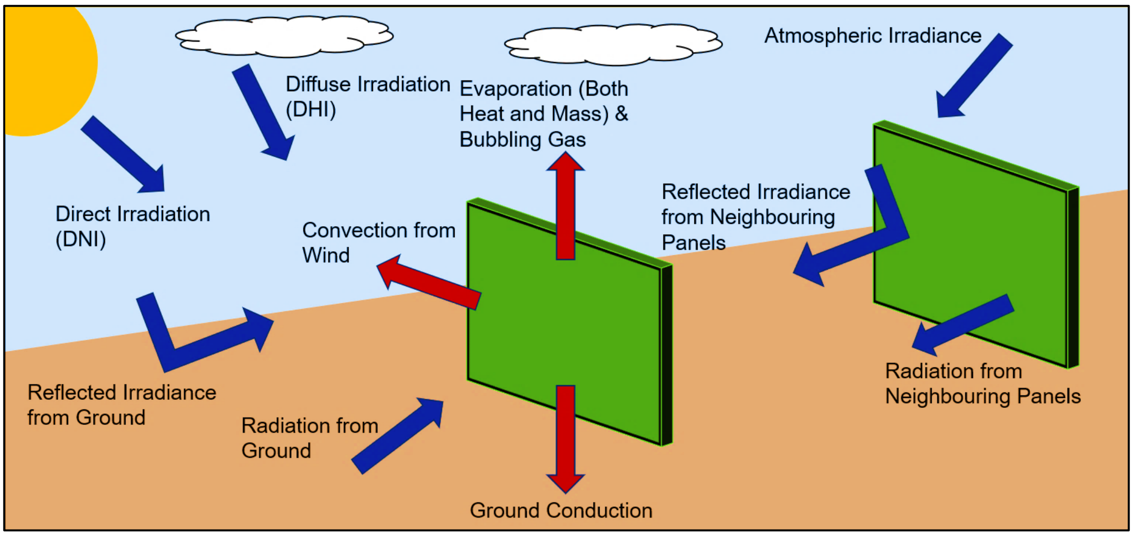

Figure 3 Diagram of heat fluxes for flat plate bioreactor model.

3. Results and Discussion

3.1 Large Scale Simulations

A 100-hectare scale was used to assess the algal growth and carbon sequestration potential in a Pilbara coastal environment. Land usage was calculated with 1.1 m spacing between ORP ponds and 1 m of ground area per 3.85 m of PBR vertical panel area (Norsker et al., 2011).

Two cases were simulated for the PBR with equal land usage. Case 1 is a realistic scenario, with larger panels leading to a lower number required for 100 hectares of ground coverage. Case 2 is an ideal case, where smaller panels provide higher algal growth rates, however requiring a prohibitively large number of panels. The second case it is undertaken in order to assess a theoretical maximum level of production for the PBR. Dimensions are displayed below in table 1.

Data from the years 2020 and 2023 were used, as they were the only complete years within the dataset. The results for both years in the Pilbara coastal location were then simulated, with an average value used for the techno-economic analysis.

Configuration	**ORP**	**PBR**	
Case	**1**	1	**2**
Biomass Production (kt)	2.6	2.0	9.0
CO_2 Consumption (kt)	3.8	2.4	9.5
Water Consumption (ML)	2.2	1.7	1.8
NH_3 Consumption (t)	0.12	73	285
DAP Consumption (t)	0.09	60	233

Table 2 Average values for the simulated production and consumption rates for both configurations.

Considering total greenhouse gas emissions of a typical 2-train LNG facility may be in the order of 3.5 MTPA, the maximum carbon sequestration potential from algal carbon sequestration in this study account for approximately 0.3% reduction annually. However, addressing climate change requires multiple solutions, and viable technologies that produce beneficial products should be further explored.

3.2 Techno-Economic Analysis

The techno-economic analysis was based on values determined by Norsker et al. (2011), as in the previous study by Choong (2023). Technology learning curves were employed to estimate the change in price over time. The prices from the study were given in 2011 Euros, therefore adjustments were made, resulting in the cost of €1.00 in 2011 being worth $2.22 AUD in 2024.

The learning curves were applied to the capital cost of both the ORP and PBR. OPEX does not have the same learning curve effect as CAPEX, thus were exempt, however the energy consumption of the PBR was included as it is assumed that there is a large amount of inefficiency associated with power demand.

A learning rate is required for the construction of a learning curve. These values can be estimated based on the Technological Readiness Level (TRL) of the technology. The estimated TRLs for each quantity are seen below.

Technology	Estimated TRL	Learning Rate	Reasoning
ORP CAPEX	9	5%	Commercially available, can be scaled out.
PBR CAPEX	6	10%	Has had larger scale implementation, but still many downfalls in terms of cost efficiency, energy consumption and process control.
PBR Power	-	4.35%	Based on a value from Rubin et al. (2007), an average value for CO_2 capture facilities.

Table 3 Estimated technology learning rates for each quantity.

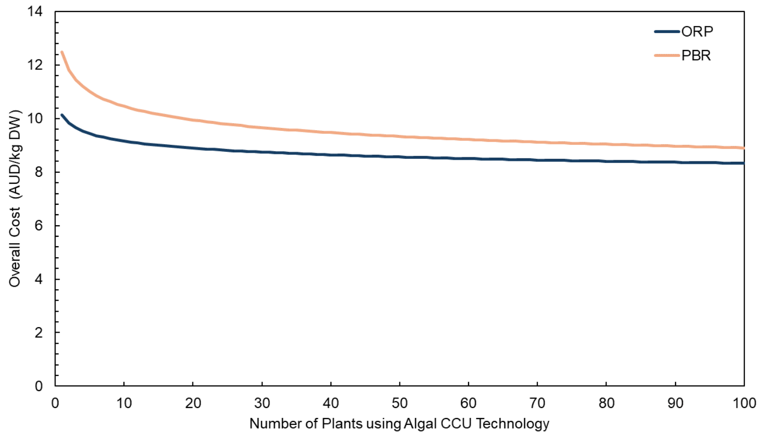

Figure 3 Technology learning curve for both ORP and PBR, based on number of plants employing the use of technology.

The cost of a PBR is projected to stay above the price of the ORP, since the power cost is the highest contributing factor to the price and is only forecast to decrease at a lower rate than the ORP CAPEX.

The OPEX cost per kilogram of algae dry weight was determined, after the Australian Carbon Credit Units (ACCUs) are accounted for. The amount of money received per ACCU was be assessed on a current value ($35.20 AUD) and a prospective value ($60 AUD) (Carbon Market Institute, 2024).

Cost (AUD/kg DW)	ORP	PBR
OPEX + Power	3.87	6.93
Current ACCU	-0.05	-0.04
Prospective ACCU	-0.09	-0.07
Current Cost	3.82	6.89
Prospective Cost	3.78	6.86

Table 4 Price estimates per kilogram of microalgae dry weight (DW) after credit from ACCUs.

The effect of the ACCU price per kilogram of production does not cause a significant change to the cost of the microalgae system. However, over the course of a year, the expenditure avoided through these ACCUs would total to be a substantial amount.

4. Conclusions and Future Work

In a simulation of a 100-hectare microalgae farm, the ORP outperformed the PBR in biomass production, carbon sequestration, and nutrient consumption. An ideal PBR case was also simulated, showing it could vastly outperform the other two, however with a prohibitively large number of panels. This suggests that PBRs may surpass ORPs under optimized conditions.

The cost per kilogram of dry microalgae production was estimated to decrease from $10.15 AUD and $12.49 AUD for ORP and PBR respectively, to $8.57 AUD and $9.33 AUD, through technological advancements. Excluding capital costs, the operational cost for ORP is $3.78-$3.82 AUD per kilogram with ACCU contributions, while PBR ranges from $6.86-$6.89 AUD due to significantly higher power consumption.

At this current stage of investigation, the use of algal biomass cultivation does not appear to be economically feasible for implementation in the model facility. If these technologies can prove to become more efficient over time, the use of biological carbon sequestration in the model facility may become feasible in the future.

This project decided to focus on the first two aims, to provide a foundation for future projects. Further research could explore end-of-life uses for the algal biomass, as well as experimental validation of the results, however this would require cultures of sufficient size. Access to company-specific equipment costing would enable a more in-depth economic analysis.

5. Acknowledgements

I would like to express my deep appreciation for both my CEED mentor, Luke McCauley, and academic supervisor, Liah Coggins. Thank you for not only supporting me throughout the project, but making it truly an enjoyable experience.

6. References

Carbon Market Institute. (2024). *Carbon Market Report 2024*. https://carbonmarketinstitute.org/app/uploads/2024/04/2024_CMI-Westpac_Carbon-Market-Report.pdf

Choong, C. (2023). *Biological Carbon Sequestration: Algae Biomass Farming*. University of Western Australia]. Perth, Australia..

Greene, J. M. (2024). CSU Algae Model. *Github repository*. https://github.com/jonahgreene01

Greene, J. M., Quiroz, D., Compton, S., Lammers, P. J., & Quinn, J. C. (2021). A validated thermal and biological model for predicting algal productivity in large scale outdoor cultivation systems [Article; Early Access]. *Algal Research-Biomass Biofuels and Bioproducts*, *54*, 15, Article 102224. https://doi.org/10.1016/j.algal.2021.102224

Norsker, N.-H., Barbosa, M. J., Vermuë, M. H., & Wijffels, R. H. (2011). Microalgal production — A close look at the economics. *Biotechnology Advances*, *29*(1), 24-27. https://doi.org/https://doi.org/10.1016/j.biotechadv.2010.08.005

Rubin, E. S., Yeh, S., Antes, M., Berkenpas, M., & Davison, J. (2007). Use of experience curves to estimate the future cost of power plants with CO₂ capture [Article; Proceedings Paper]. *International Journal of Greenhouse Gas Control*, *1*(2), 188-197. https://doi.org/10.1016/s1750-5836(07)00016-3