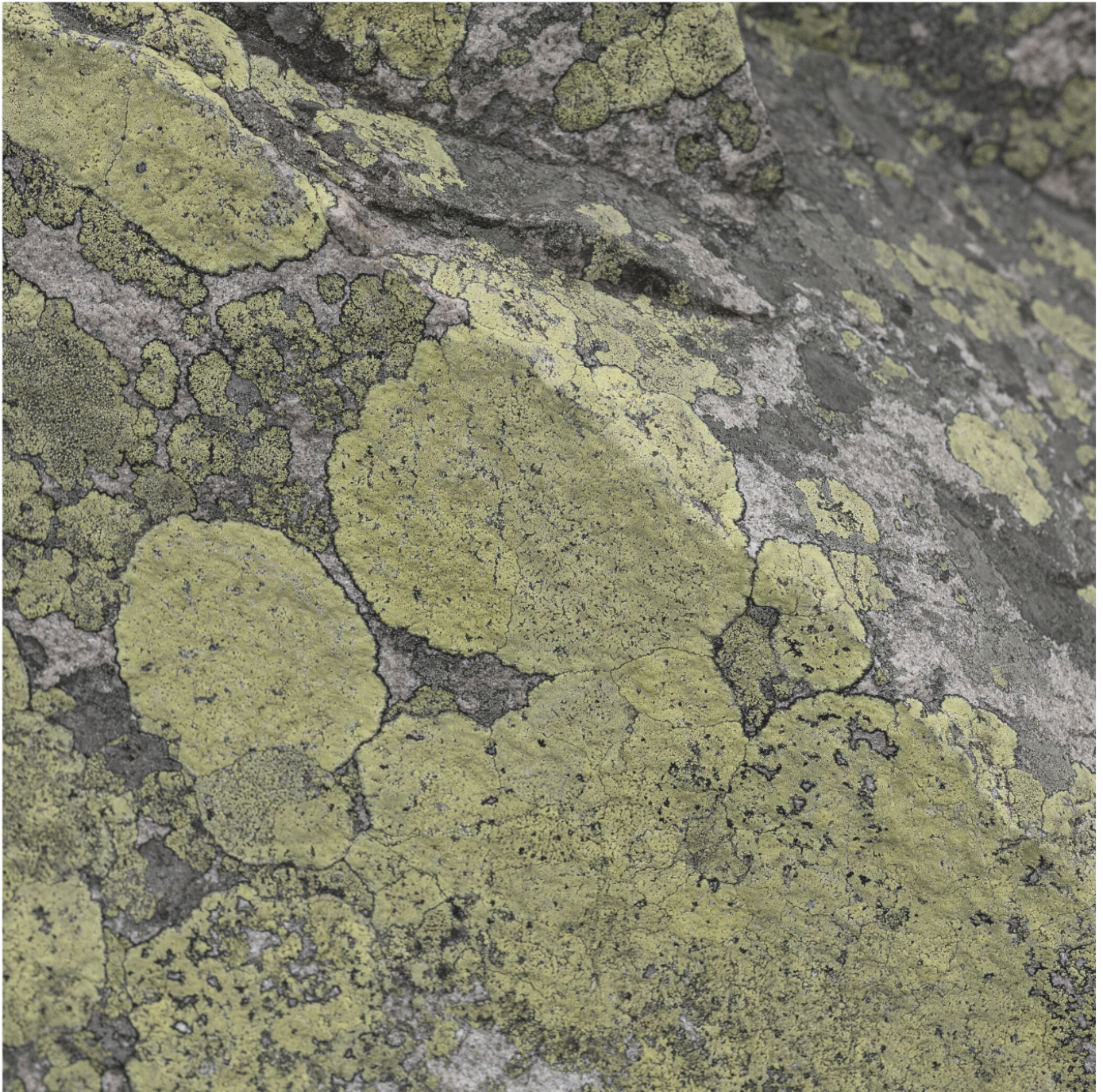


# CARBON CAPTURE COATINGS: Next Generation Biomimetic Coatings for Carbon Capture & Removal

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# Initial techno-economic and life cycle assessment of a novel algae-based coating for direct air carbon capture and sequestration

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## Executive Summary

Direct air carbon capture and storage systems (DACCS) are expected to play an important role in fighting climate change by mitigating greenhouse gas emissions from various hard-to-abate sectors such as aviation, container shipping, and the manufacturing of steel and concrete. While existing DACCS technologies have demonstrated CO<sub>2</sub> removal rates at or below the kiloton scale, high capital costs and significant energy demands represent the largest hurdles in achieving mid-century carbon removal goals of 10-20 GtCO<sub>2</sub>/yr. As DACCS technologies are developed and advanced, techno-economic analysis (TEA) and life cycle assessment (LCA) provide robust mechanisms for evaluating system performance by estimating net carbon removal and the associated costs. This study focuses on a novel biomimetic coating primarily consisting of a hydrogel seeded with microalgae biomass printed on a polyethylene substrate [1]. The coating has been developed to exploit the high photosynthetic rates of microalgae to fix atmospheric CO<sub>2</sub> into cellulose using incident solar energy. The carbon embodied in the cellulose material is converted to biochar through pyrolysis to ensure durable carbon sequestration without the need for underground storage in natural CO<sub>2</sub> reservoirs. The proposed system offers many advantages including modularity and scalability, locational flexibility, a re-usable coating formula, the potential for high water retention rates, and long periods of operation with minimal maintenance and management. Preliminary results from the modeling work suggest a carbon removal efficiency of 50% and a carbon removal cost of \$629 per tonne CO<sub>2</sub> net sequestered. The modular design of the coated substrate system and utilization of solar energy supports the rapid upscaling necessary to meet mid-century carbon removal goals with DACCS technologies.

## 1. Introduction

Anthropogenic greenhouse gas (GHG) emissions have caused the global temperature to rise approximately 1.18°C since the 19<sup>th</sup> century resulting in a multitude of devastating environmental impacts [2]. Outlined in the 6<sup>th</sup> Assessment Report from the International Panel on Climate Change (IPCC), the best path to limiting warming under 1.5°C by 2100 is to achieve a 45% reduction in human-caused CO<sub>2</sub> emissions by 2030 and to reach net-zero emissions by 2050 [3]. A number of essential sectors lack a clear pathway towards net-zero emissions. These hard-to-abate sectors make up nearly 30% of global GHG emissions and include the manufacturing of essential chemicals and materials like cement, steel, aluminum, and fertilizers, as well as heavy duty transportation industries including shipping, trucking, and aviation [4]. In order to reach large-scale and long-term removal goals of 20 billion tonnes of CO<sub>2</sub> per year in the second half of the century, costlier and less developed technologies like Direct Air Carbon Capture and Storage (DACCS) will need to be adopted at unprecedented levels [5]. The carbon capture coating examined in this study offers the potential to capture and sequester atmospheric CO<sub>2</sub> while providing valuable co-products that could reduce emissions in additional industry sectors [6].

In order to achieve removal targets of GtCO<sub>2</sub>/yr, DACCS technologies must undergo massive up-scaling. While decades of research and development have focused on the advancement of chemical solvent and sorbent technologies for DACCS systems, this study aims to assess a novel and emerging technology which exploits the biological process of photosynthesis to perform direct air capture on a large scale. We evaluate the carbon capture potential of a coated surface made from hydrogel, microalgae, nutrients, and water. The coated surface housed in modular enclosures has been designed to mimic the biological processes exhibited by lichen by converting atmospheric CO<sub>2</sub> into cellulose which accumulates in the coating over time. Many algae produce cellulose as a component of their outer cell walls, with some species such as *Chlorella* doing so in great abundance. Other bacteria are known to possess genes enabling them to export very large amounts of bacterial cellulose. When these genes are moved into algal cells, the resulting recombinant algal cells themselves create large amounts of such bacterial cellulose which is known to accumulate extra-cellularly over time. The coating is then harvested, and the constituents are separated with a chelator which allows the generated cellulose to be converted to biochar through pyrolysis. The produced biochar has many potential applications. In this study we assume the biochar is

land applied, providing an environmental service while durably sequestering the embodied carbon in the process. While still in the early stages of development, there are many predicted advantages of this novel technology including the ability to quickly reach large scale carbon removal through the utilization of non-arable land, rainwater capture, and on-site solar PV to meet the minimal energy demands of the system. Additionally, once the initial surface has been seeded and deployed, the system is designed to remove carbon from the atmosphere and build up cellulose for months to years with minimal system inputs or required maintenance. The longevity of the algal cultures contained in the coating is currently being evaluated through lab-scale experiments and the economic and environmental impacts of this parameter should be investigated further. The potentially long operational life of this biomimetic surface would allow for rapid large-scale deployment across the globe. This study aims to quantify a preliminary order of magnitude estimate of the near-term environmental and economic performance of this novel carbon capture coating using a first order system model, which serves as the foundation for integrated TEA and LCA.

## 2. Materials and Methods

### 2.1 System Boundary

The system boundary of this study is such to ensure proper evaluation of the carbon removal efficiency. This study focuses on the goal of durable long-term sequestration. Thus, the system boundary of the study encompasses all upstream and downstream activities including materials acquisition and emissions embodied in the modules and coating as well as emissions from operational energy, material replacement, maintenance, and direct emissions to air from pyrolysis. A detailed process flow diagram is presented in Figure 1, illustrating the system boundary and the mass and energy flows included in the system engineering model.

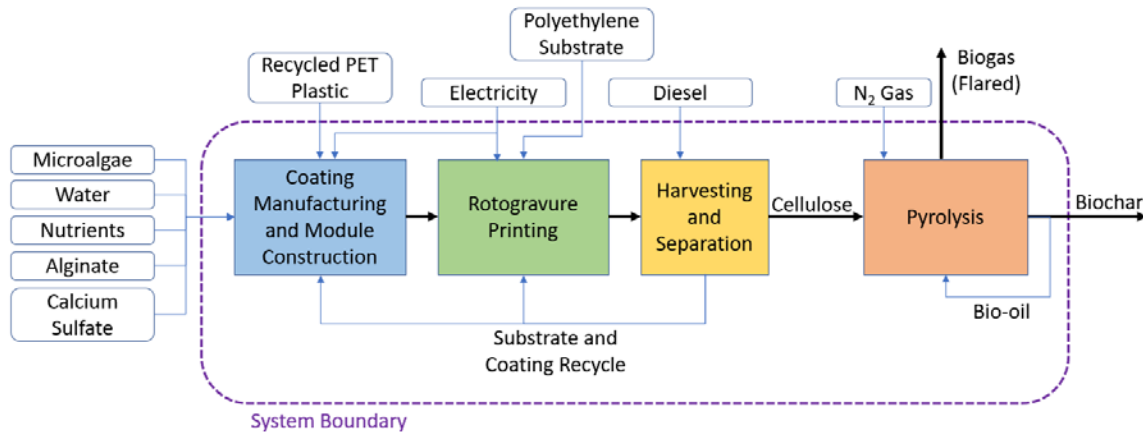


Figure 1: Process flow diagram showing the system boundary and the material and energy inputs and outputs accounted for in the system engineering model and subsequent techno-economic and life cycle assessments.

### 2.2 Functional Unit

The functional unit of this analysis is the cost of carbon sequestration in \$/tCO<sub>2</sub> net-sequestered derived from the cost of carbon capture and the carbon removal efficiency of the system, Equation 1.

$$\frac{\$}{tCO_2 \text{ net sequestered}} = \frac{\frac{\$}{tCO_2 \text{ captured}}}{\left(1 - \frac{tCO_2 \text{ emitted}}{tCO_2 \text{ captured}}\right)} \quad (1)$$

## 2.3 Process Model Development

The carbon capture and sequestration process evaluated in this study is divided into four major sub-processes including coating manufacture and module construction, rotogravure printing, harvesting and separation, and pyrolysis (Figure 1). After printing, the coating is left protected in the enclosure with minimal maintenance over the course of its lifetime. At the end-of-life, coating components are recycled, and biomass rich cellulose is charred for stable carbon sequestration.

### 2.3.1 Coating Manufacturing and Module Construction

The coating analyzed in this study consists of water (97% w/w), microalgae (0.09% w/w), alginate (1.29% w/w), calcium sulfate (1.38% w/w), tetrasodium pyrophosphate (0.09% w/w), and BG-11 nutrient formula (0.15% w/w). Critical to the design of the carbon capture coating is the ability to reversibly polymerize and to depolymerize the polymer matrix, thereby allowing the paint components to be received and reused, including the algae. This is accomplished by using ionically polymerized hydrogels like alginate that are ionically bonded (unlike more widely-used covalently bonded paint polymers) by substituting calcium ions for the naturally-occurring sodium in the alginate. Once the algae are released from the hydrogel, the carbon in the biomass can be converted into a form of durably-sequestered carbon such as biochar.

Initial algal cultures are obtained from commercial algae cultivation centers, or similar facilities to be built on site. These initial cultures are amplified to a dense inoculum level and used to formulate the paint combining the algal cells with hydrogel coating monomers, micronutrient solutions, calcium solutions, and polymerization retardants just prior to applying the formula to a polyethylene substrate using a printing jig and drawdown squeegee. After allowing a short time for the paint to cure, painted sheets are rolled into spools, transported, and installed in the modules using an integrated roller system. The total surface area of sheets installed in each module is determined by the maximum amount of carbon fixation based on the available quantity of incident solar radiation and carbon pulldown rate of the coating.

The coated sheets are protected from the environment by a transparent modular enclosure made of recycled PET plastic. In essence the enclosure acts as a miniature green house that minimizes empty space and allows for modular deployment of the system. The modules are designed to achieve a terrarium-like environment which allows ample gas exchange, controlled humidity, and the passage of light energy required to sustain the algal cultures in the coating. While a number of module designs are currently being tested, this study assumes the use of a module with a built-in network of tensioned rollers arranged in a serpentine fashion allowing rapid installation and harvesting of coated sheets at the end of their functional life. It was assumed that air conditioning would not be required to maintain temperature and relative humidity within acceptable ranges. Each module is 10 m long by 1 m wide by 1.5 m high with a wall thickness of 10 mm and houses up to 630 m<sup>2</sup> of coated substrate.

### 2.3.2 Rotogravure Printing

Rotary printing presses, which can be calibrated for use in many applications, deposit the coating onto a single side of large 0.8 m wide sheets of woven polyethylene substrate at a deposition weight of 3.8 kg/m<sup>2</sup> [7], [8]. Following printing, the coated sheets are rolled into spools to be transported and installed in the modular coating housings. Energy consumption for printing was determined from an interview with an industry expert. Electricity consumption for the rotogravure printing process was assumed to be 0.6 kJ/m<sup>2</sup> based on a 15-kW machine with a 1,500 m<sup>2</sup>/min capacity.

### 2.3.3 Harvesting and Separation

The sheets are rolled out of the coating housing using a forklift attachment and are loaded onto a flatbed trailer for transport to a centralized reclamation facility. The mean transportation distance was calculated assuming a circular facility layout with the reclamation facilities in the center making the mean round trip transportation distance equal to the radius of the facility (3.9 km). At the point of harvesting, the cellulose in the coating is 40% of the total coating mass. A majority of the remaining mass is water with less than 2% being other

coating materials. The coating is stripped from the substrate using a chelating solution. The chelating step that disassociates the alginate polymers, micronutrients, algae biomass, and accumulated cellulose is achieved with metal chelators such as ethylenediamine tetra-acetic acid (EDTA). EDTA is a polyprotic acid containing four carboxylic acid groups and two amine groups with ion-pair electrons that ionically bond to calcium (and other metal ions). Following the chelating step, the EDTA can be reclaimed and re-used. Initial lab-scale experiments indicate the separation process requires 0.6 L/kg coating of 130g/L Sodium citrate solution and 0.3 L/kg coating of 90g/L EDTA Solution.

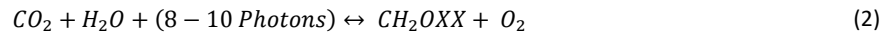
After the coating constituents are stripped from the substrate and separated, the majority of the microalgae biomass and associated cellulose are sent to a pyrolysis furnace to produce biochar while the water and remaining coating constituents are recycled to the printing facility where any losses are replenished by virgin material. Coating material recovery rates and chelating solution recycle rates are specified in Table 1.

### 2.3.4 Pyrolysis

Pyrolysis will occur at the centralized processing facility immediately following component separation. Pyrolysis is commonly used in the bio-energy sector to produce bio-oil, but a pyrolysis unit can be optimized for maximum biochar production with a coproduct of bio-oil [9]–[11]. Bio-oil was modeled as the fuel source for pyrolysis. With an annual bio-oil output of 348,000 t/yr and an annual energy demand of 452 thousand MWh/yr (0.27 kWh/kg feed) for the pyrolysis unit, the combustion of bio-oil would be sufficient to power the pyrolysis unit assuming a HHV of 30 MJ/kg and heater efficiency of 90% [12]. Phase yields and associated carbon streams are specified in Table 1.

## 2.4 Carbon Capture Coating Performance

Since the algae in the coating fix atmospheric CO<sub>2</sub> into cellulose through photosynthesis, the major limiting factors in the coating's carbon removal rate are the total amount of incident solar radiation in the location of deployment and the photosynthetic efficiency of the microalgae. Calculations to determine the solar energy demand per kg of atmospheric CO<sub>2</sub> fixed into cellulose are based on the algae growth model developed by Greene et al. [13]. Estimation of the energy demand begins with the following chemical reaction representative of the photosynthetic process:



This assumed value of 8-10 photons per CH<sub>2</sub>O represents the theoretical minimum for idealized systems and doesn't incorporate real-world losses [13]. Thus, the solar energy demand required to fix 1 kg of atmospheric CO<sub>2</sub> via photosynthesis,  $E_{C_{fixation}}$ , was derived with the following equation based on the methodology of Weyer et al. [14]:

$$\left( \frac{1 \text{ mol } CO_2}{0.044 \text{ kg } CO_2} \right) * \left( 8 \frac{\text{mol Photons}}{\text{mol } CO_2} \right) * \left( 0.2253 \frac{\text{MJ}}{\text{mol Photons}} \right) * \frac{1}{\varepsilon_T} * \frac{1}{\varepsilon_U} = E_{C_{fixation}} \frac{\text{MJ}}{\text{kg } CO_2} \quad (3)$$

In Equation 3, the photon energy of 0.2253 MJ mol<sup>-1</sup> photon was obtained from Weyer et al. [14] and corresponds to an average wavelength of 531 nm. This term represents the wavelength-weighted average photon energy within the portion of the solar spectrum utilizable for photosynthesis (also called photosynthetically active radiation (PAR)). In Equation 3,  $\varepsilon_T$  represents the photon transmission efficiency to account for a portion of the incident radiation that is reflected and absorbed by the transparent enclosure housing the coated surface, and  $\varepsilon_U$  is the photon utilization efficiency to account for the fraction of incident energy used for cell maintenance and repair rather than photosynthesis. Regionally-resolved estimates of Global Horizontal Irradiance (GHI) in kWh/m<sup>2</sup> were obtained from Solargis [15] and converted to PAR by assuming 45.8% of solar irradiance lies in the photosynthetic spectrum [14].

To maximize carbon uptake by the system and minimize costs, the surface area of coating per m<sup>2</sup> of ground area (packing density) was optimized. Equations 3 and 4 govern the theoretical maximum carbon uptake by the system per square meter of facility footprint.

$$CO_{2\max} \left( \frac{kg\ CO_2}{m^2s} \right) = \frac{GHI \left( \frac{MW}{m^2} \right)}{E_{c_{fixation}} \left( \frac{MJ}{kg\ CO_2} \right)} = constant \quad (4)$$

Equation 5 optimizes the packing density to minimize material requirements.

$$PD_{min} \left( \frac{m^2}{m^2} \right) = \frac{CO_{2\max} \left( \frac{kg\ CO_2}{m^2s} \right)}{\dot{R}_{uptake} \left( \frac{kg\ CO_2}{m^2s} \right)} \quad (5)$$

Since the maximum carbon uptake per m<sup>2</sup> of ground area is ultimately limited by the total amount of incident solar energy (Equation 4), the minimum surface packing density,  $PD_{min}$ , and the carbon uptake rate of the coating,  $\dot{R}_{uptake}$  (mmol CO<sub>2</sub> m<sup>-2</sup> hour<sup>-1</sup>), are inversely proportional (Equation 5). The surface uptake rate has a realistic maximum of 10 mmol CO<sub>2</sub> m<sup>-2</sup> hour<sup>-1</sup> based on lab-scale experiments with the current coating formula. The realistic maximum packing density is dependent on design geometry due to self-shading. It is necessary to maximize the carbon uptake rate of the coating ( $\dot{R}_{uptake}$ ) to allow more spacing between sheets of coated substrate avoiding geometric constraints that lead to shading. The minimum surface packing density for complete solar energy utilization is rather high and is geometrically difficult to achieve without over exposure of some algae and shading of others. The actual carbon uptake per m<sup>2</sup> of ground area is determined from equation 6.

$$\begin{aligned} \text{if } PD \left( \frac{m^2}{m^2} \right) < PD_{min} \left( \frac{m^2}{m^2} \right) & \quad CO_{2\text{uptake}} = \dot{R}_{uptake} \left( \frac{kg\ CO_2}{m^2s} \right) * PD \left( \frac{m^2}{m^2} \right) \\ \text{if } PD \left( \frac{m^2}{m^2} \right) \geq PD_{min} \left( \frac{m^2}{m^2} \right) & \quad CO_{2\text{uptake}} = CO_{2\max} \left( \frac{kg\ CO_2}{m^2s} \right) \end{aligned} \quad (6)$$

Achieving maximum packing density while allowing full utilization of incident solar radiation represents a significant hurdle that must be addressed through innovative engineering and pilot-scale testing. The water-based coating evaluated in this study is staged to operate in arid climates, thus the water retaining characteristics of the coating were assumed to quantify the makeup water required to operate the system. While the housings were designed to create terrarium-like environment and increase the relative humidity within the modules, water loss through evaporation is still expected to occur. Annual water losses (expressed as a percentage of the initial water in the coating) were defined for each modeling scenario and are presented in Table 1.

## 2.5 Critical Modeling Assumptions

Results presented in this study are for a facility yielding a net carbon removal of approximately 1 million tonnes (Mt) CO<sub>2</sub> per year with total facility size dependent on a number of critical assumptions. The facility was modeled in the Desert Southwest of the United States of America where the mean horizontal irradiance is 8,150 MJ m<sup>-2</sup> yr<sup>-1</sup> [15]. Modules housing the carbon capture coatings cover 75% of the facility footprint, and a road network for coating harvest in addition to centralized coating manufacture, reclamation, and pyrolysis facilities occupy the remaining space. In order to bridge the gap between benchtop experiments and an Nth scale facility capable of removing 1 MtCO<sub>2</sub>/yr, a number of critical assumptions were defined within the model. The critical parameters and assumed values used for the modeling work are presented in Table 1.

Table 1: Critical modeling assumptions for a 1 MtCO<sub>2</sub>/yr removal facility

| Parameter                               | Units   | Value   | Reference         |
|---|---|---------|-------------------|
| <b>Physical Constraints</b>             |   |         |                   |
| <u>Algae:</u>                           |   |         |                   |
| Photon Transmission Efficiency          | %   | 90%     | [14]              |
| Photon Utilization Efficiency           | %   | 65%     | [14]              |
| <u>Solar Energy:</u>                    |   |         |                   |
| Full-spectrum Solar Energy              | MJ m <sup>-2</sup> year <sup>-1</sup>                   | 8150    | [15]              |
| <b>Design Parameters</b>                |   |         |                   |
| <u>Facility Operation:</u>              |   |         |                   |
| Operating Days                          | days  | 330     | Assumption        |
| Time to Harvest                         | years or months   | 5 years | Assumption        |
| <u>Coating Design/Performance:</u>      |   |         |                   |
| Carbon Removal Rate                     | mmol CO <sub>2</sub> m <sup>-2</sup> hour <sup>-1</sup> | 5       | Experimental Data |
| Annual Water Retention Rate             | % Initial water retained after 1 yr. of deployment      | 75%     | Assumption        |
| <u>Pyrolysis Performance:</u>           |   |         |                   |
| Cellulosic Carbon to Biochar            | %   | 60%     | [9]–[11]          |
| Cellulosic Carbon to Bio-oil            | %   | 35%     | [16]              |
| Cellulosic Carbon to Bio-vapors         | %   | 5%      | Assumption        |
| <u>Coating Reclamation Performance:</u> |   |         |                   |
| Coating Material Recovery               | %   | 90%     | Assumption        |
| Chelating Solution Recovery             | %   | 90%     | Assumption        |

## 2.6 Capital Expenses

Capital costs were quantified for all components of the system including the purchasing and preparation of land, manufacturing of coating constituents and housings, and equipment for deployment, maintenance, harvesting, separation, and pyrolysis. Capital costs are referenced from literature and adjusted to the appropriate capacity using a scaling parameter and exponent where appropriate. The chemical engineering plant cost index (CEPCI) is used to bring all referenced costs to 2019 dollars [17]. Capital cost assumptions are presented in Table 2.

Table 2: Total capital cost of major equipment for a 1 MtCO<sub>2</sub>/yr removal facility

| Major Capital Expenses          | Unit Cost                     | Cost      | Cost Year | Reference |
|---------------------------------|-------------------------------|-----------|-----------|-----------|
| Recycled PET Modular Enclosures | \$50/m <sup>2</sup> footprint | \$2,341MM | 2019 USD  | [18]      |
| Rotogravure Printing Machines   | \$143K/printer                | \$0.143MM | 2019 USD  | Estimate  |
| Forklifts                       | \$30K/forklift                | \$0.926MM | 2019 USD  | [19]      |
| Flatbed Semis                   | \$100K/semi                   | \$6.20MM  | 2019 USD  | [20]      |
| Separation/Chelating Units      | \$143K/unit                   | \$0.143MM | 2019 USD  | Estimate  |
| Pyrolysis Units                 | \$62MM/unit                   | \$249MM   | 2019 USD  | [12]      |

The cost of the modular enclosures was quantified on a per m<sup>2</sup> basis and includes the cost of a small emergency heater, rainwater capture system and reservoir, and a system of rollers to allow for rapid deployment and harvesting of coated surfaces. Greenhouse structures range in cost from \$87/m<sup>2</sup> to \$128/m<sup>2</sup> and provide the most direct comparison to the planned module housing [18]. The coating modules are assumed to be cheaper than standard greenhouse enclosures as the snap-together components do not require a steel frame, utilize recycled PET material, contain minimal equipment, and can be mass produced with an assembly line.

The full-scale facility is constructed incrementally. For example, with a grow out period of 5 years between harvests, 1/5<sup>th</sup> of the facility is opened annually for 5 years. An initial investment of enough coating materials and substrate for 1/5<sup>th</sup> of the total facility footprint is incurred each year for the first 5 years of operation. The first harvest takes place in year 6, when all coated surfaces from year one are collected, separated, sent through pyrolysis, and land applied. From this year forward the facility operates in a continuous fashion, harvesting 20% of the total acreage annually (32 acres/day). Running the facility in this manner reduces the burden



on printing, recycling, and minimizes the required pyrolysis capacity. The printing and harvesting infrastructure are therefore sized to resurface only 20% of the total substrate area annually and the pyrolysis unit is sized to process 5 years of accumulated cellulose from only 20% of the total substrate area annually. Cost for printing was determined from an interview with an industry expert. Based on a machine printing capacity of  $1122 \text{ m}^2 \text{ min}^{-1}$ , the facility would require one high-speed printing machine.

Capital costs were quantified for equipment needed to harvest and transport coated surfaces from housing modules to the processing facility, as well as the equipment needed for coating separation and reclamation. For the  $1 \text{ MtCO}_2/\text{yr}$  facility, two trucks and one forklift were included for every 500 acres of facility footprint for hauling. The cost of reclamation equipment was approximated as an additional rotogravure printer fitted with the equipment necessary to strip the coating from the substrate and separate the constituents for further processing and re-use.

The cost of pyrolysis equipment is adapted from previous work in the bio-energy sector [12]. The cost of a  $41,667 \text{ kg hr}^{-1}$  capacity pyrolysis unit was sourced from Dutta et al. [12] and scaled based on total calculated processing capacity using a scaling exponent of 0.8.

Land was assumed to cost  $\$3,000/\text{acre}$ , representative of low-value non-arable land in the Desert Southwest or Gulf Coast of the United States [21]. Site development including land grading, office construction, and project contingency were assessed as a percentage of equipment and infrastructure costs based on the work of Davis et al. [21].

## 2.7 Operational Expenses

### 2.7.1 Variable Operational Expenses

Variable operational costs include electricity for printing machines, water pumps, and pyrolysis conveyers, diesel for harvesting, nitrogen as an inert gas for pyrolysis, well water, and the various coating constituents necessary to re-surface substrate to account for inefficiencies in the coating reclamation process. Variable operational costs for the  $1 \text{ MtCO}_2/\text{yr}$  system are summarized in Table 3.

Table 3: Major variable operational costs defined for a  $1 \text{ MtCO}_2/\text{yr}$  removal facility

| Parameter   | Units             | Value | Reference    |
|---|-------------------|-------|--------------|
| <b>Major Material Costs</b>   |                   |       |              |
| <u>Energy Costs:</u>  |                   |       |              |
| Electricity (On-site Solar PV)  | \$/kWh            | 0.09  | [22]         |
| Natural Gas   | \$/1000 SCF       | 5.10  | [21]         |
| Diesel  | \$/gallon         | 3.03  | [23]         |
| <u>Coating Constituents:</u>  |                   |       |              |
| Polyethylene Substrate  | \$/m <sup>2</sup> | 0.18  | Assumption   |
| Microalgae Biomass  | \$/tonne AFDW     | 1500  | [24]         |
| Other Constituents (listed below):  | \$/kg dry wt.     | 0.16  | Assumption*  |
| Alginate  |                   |       |              |
| Calcium Sulfate   |                   |       |              |
| Tetrasodium Pyrophosphate   |                   |       |              |
| BG-11   |                   |       |              |
| <u>Chelating solution:</u>  |                   |       |              |
| Sodium Citrate  | \$/kg             | 0.50  | Assumption** |
| EDTA  | \$/kg             | 0.70  | Assumption** |
| <u>Other Materials:</u>   |                   |       |              |
| Nitrogen  | \$/kg             | 0.16  | [25]         |
| Well Water  | \$/m <sup>3</sup> | 0.40  | [21]         |
| Biochar Selling Price   | \$/tonne          | 100   | [26]         |
| *Cost of "Other Constituents" based on current lab expenses with significant bulk discounts applied |                   |       |              |
| **Assumption based on commercially available online products  |                   |       |              |

Nitrogen for pyrolysis was assumed to come from an onsite air separation unit. The modeling of this unit was considered outside the scope of the study and the costs for nitrogen listed in Table 4 for the three scenarios represent the levelized cost of onsite nitrogen production. Annual water consumption for the system was calculated as 11.1 million m<sup>3</sup>/yr based on the assumed coating composition, water retention rates, and losses during the coating separation and recycling process.

### 2.7.2 Fixed Operational Expenses

Fixed operational expenses consist of labor and labor burdens, maintenance, and insurance. The rotogravure printing process in which the carbon capture coating is deposited on the substrate would require 5 operators and would operate on a continuous 24-hour schedule. Maintenance and management were assumed to be minimal for the 5-year lifetime from the moment the coatings have been deployed until they are harvested. 240 field laborers would be responsible for monitoring the coating modules and performing general maintenance tasks such as washing dust and debris from the coating housings, replacing damaged surfaces, and checking maintenance indicators for low water levels, low RH, and light attenuation from dust. Each worker would manage roughly 40 acres of the facility.

Harvesting is assumed to be a labor-intensive process. The 240 field laborers also serve as coating harvesters. Assuming a 1-year grow out between harvests, roughly 5.5 acres would be harvested daily. Teams of two laborers would be responsible for harvesting 18.5 housing modules daily by rolling up the surfaces into spools and staging them for collection along the service roads. Several collection teams equipped with forklifts and flatbed semi-trucks would drive along the service road, collecting the rolls and transporting them to the centralized processing facility. Once rolls of coated surfaces have arrived at the centralized processing facility, the separation and reclamation processes require an additional 5 operators working rotating shifts to operate on a continuous 24-hour schedule. All required personnel are outlined in Table 4.

*Table 4: Labor requirements for a 1 MtCO<sub>2</sub>/yr removal facility*

| Parameter                       | Base Salary         | Reference |
|---------------------------------|---------------------|-----------|
| <b>Labor Costs</b>              |                     |           |
| Facility manager                | \$73,613            | [27]      |
| Operations manager              | \$73,613            | [27]      |
| Operations specialist           | \$73,613            | [27]      |
| Coating machine operator        | \$42,900            | [27]      |
| Harvest supervisor              | \$73,613            | [27]      |
| Module/harvest laborer          | \$33,500            | [27]      |
| Pyrolysis operator              | \$42,900            | [27]      |
| Site engineer                   | \$73,613            | [27]      |
| Pyrolysis engineer              | \$73,613            | [27]      |
| Maintenance specialist          | \$73,613            | [27]      |
| Labor Burdens                   | 90% of Base Salary  | [21]      |
| <b>Total Annual Labor Costs</b> | <b>\$16,475,288</b> |           |

The facility capacity, as reflected in operating days, accounts for maintenance of engineered equipment at the centralized facilities. While equipment is expected to need regular general maintenance, the coatings are in operation 24/7 from the moment they are deployed until they are harvested. Insurance and maintenance are assessed as 0.7% and 3% of total direct capital (TDC) expenses, respectively [21].

## 2.8 Techno-Economic Analysis Methodology

The techno-economic analysis was performed using a 30-year discounted cash flow rate of return (DCFRROR) model to determine the minimum cost of carbon removal in \$/tCO<sub>2</sub> net sequestered. A 7 year Modified Accelerated Cost Recovery System (MACRS) depreciation schedule was applied to the total equipment capital investment for all equipment including the pyrolysis system. The MACRS depreciation scheme was chosen to be

consistent with existing TEA studies for numerous Nth scale bio-energy systems and to allow comparison of the results to alternative DACCS technologies. Furthermore, the cash flow model assumed a 10% internal rate of return (IRR), and an income tax rate of 35% over the 30-year time horizon for the economic analysis. The TEA assumed 40% equity, a loan term of 10 years, and an interest rate of 8%. The working capital was assumed to be 5% of the total system capital expenditure. Revenue generated from the biochar product was incorporated into the analysis to determine a minimum cost of carbon capture such that a net present value of zero was achieved based on an internal rate of return of 10%. Results are expressed with the metric USD per tonne of atmospheric CO<sub>2</sub> durably (100 years) sequestered.

## 2.9 Life Cycle Assessment

### 2.9.1 Methodology

This LCA study is attributional and operates under the assumption that the primary production of materials is allocated to the primary user and recycled materials are provided burden free to subsequent processes. LCI data were gathered, system boundaries were developed, and burdens and credits have been allocated in accordance with ISO 14040 standards [28]. All scope 1 and 2 operational emissions are accounted for. This project has a large upfront burden for manufacturing and assembling infrastructure with minimal operational emissions. Emissions associated with major infrastructure including the recycled PET modules and initial coating and substrate constituents were included in the system boundary, while emissions associated with the production of machinery including forklifts, semi-trucks, printing machines, and pyrolysis units were excluded from the system boundary and assumed to be negligible compared to emission for the initial coating material constituents, the coating substrate, and the modular coating housings due to the mass of the materials.

### 2.9.2 Life Cycle Inventory Data

Lifecycle inventory (LCI) data was acquired directly from the EcoInvent database (version 3.7) [29] whenever available. Materials acquisition and manufacturing of the PET coating housings was approximated using a surface area of 53 m<sup>2</sup>/module, a thickness of 10 mm, 405 modules per acre and assuming the use of extruded recycled polyethylene terephthalate (PET) plastic. Substrate material was modeled as polyester fiber made from recycled polyethylene granulate. The production of microalgae biomass and alginate were assumed to result in net-zero emissions based on the modeling work of Greene et al. [13]. Emissions for BG-11 were approximated using ammonia and DAP as a proxy, obtaining total required mass based on delivering equivalent nitrogen and phosphorous content to the coating. LCI data are summarized in Table 5.

*Table 5: Life Cycle Inventory (LCI) data obtained from the EcoInvent Database*

| Material                  | LCI Data (kg CO <sub>2</sub> -eq/kg XX)                                      | Reference |
|---------------------------|--|-----------|
| Fiber spinning process    | 1.07 kg CO <sub>2</sub> -eq/kg feedstock                                     | [29]      |
| HDPE extrusion process    | 1.08 kg CO <sub>2</sub> -eq/kg feedstock                                     | [29]      |
| Recycled HDPE granulate   | 0.71 kg CO <sub>2</sub> -eq/kg polyethylene                                  | [29]      |
| Untreated well water      | 0.22 kg CO <sub>2</sub> -eq/m <sup>3</sup>                                   | [29]      |
| Tetrasodium pyrophosphate | 2.33 kg CO <sub>2</sub> -eq/kg Na <sub>4</sub> P <sub>2</sub> O <sub>7</sub> | [29]      |
| Calcium sulfate           | 0.74 kg CO <sub>2</sub> -eq/kg CaSO <sub>4</sub>                             | [29]      |
| Ammonia                   | 5.33 kg CO <sub>2</sub> -eq/kg   | [29]      |
| DAP                       | 3.6 kg CO <sub>2</sub> -eq/kg DAP  | [29]      |
| Nitrogen                  | 0.48 kg CO <sub>2</sub> -eq/kg N <sub>2</sub> gas                            | [29]      |
| Solar PV                  | 0.056 kg CO <sub>2</sub> -eq/kWh   | [29]      |
| Transportation            | 0.22 kg CO <sub>2</sub> -eq/tonne*km   | [29]      |

### 3. Results

The total capital expenditure and annual operational expenses of the system were combined with the CO<sub>2</sub> capture efficiency to determine the total capture and sequestration cost per tonne CO<sub>2</sub> net-sequestered. After accounting for all sources of re-emission, the capture and sequestration cost shown in Figure 2 represents the cost to transform 1 tonne of atmospheric CO<sub>2</sub> into biochar using a coated substrate system capable of achieving a net removal of 1,000,000 tonnes CO<sub>2</sub> per year. Additionally, the results in Figure 2 represent the minimum product selling price (MPSP) or the value of sequestered CO<sub>2</sub> that yields a 10% internal rate of return over the 30-year life of the plant.

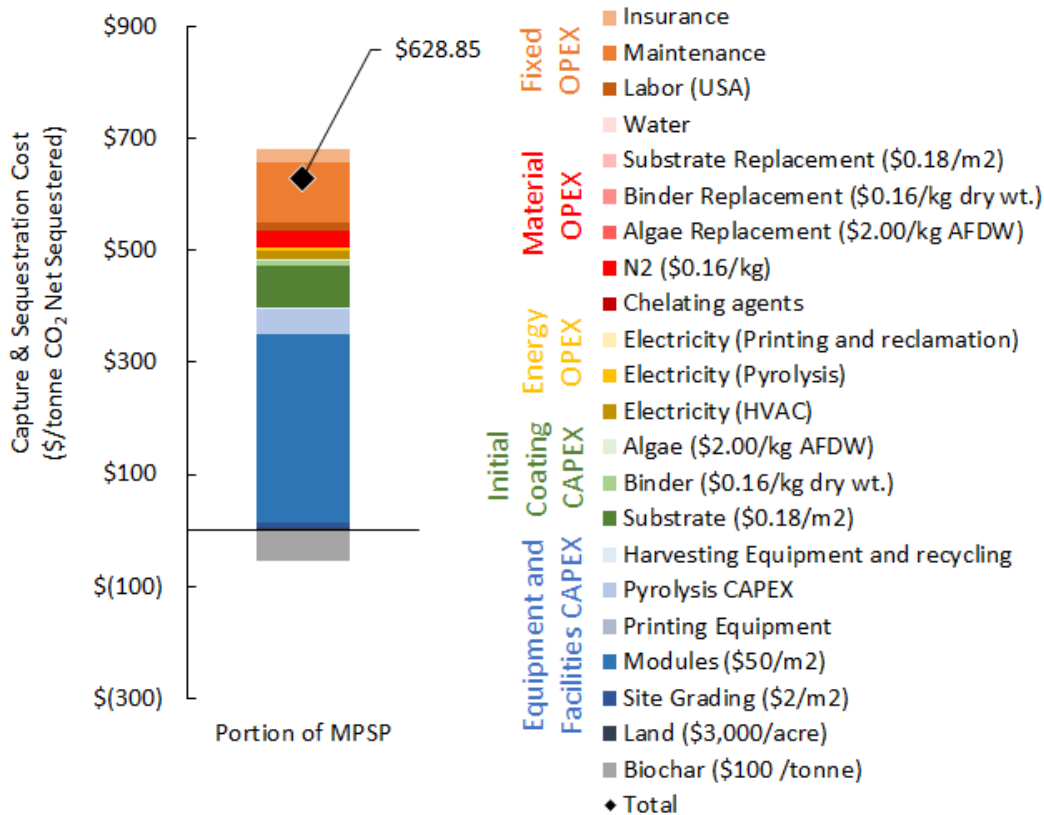


Figure 2: Cost of CO<sub>2</sub> capture and sequestration (\$/tCO<sub>2</sub> net sequestered) utilizing the carbon capture coatings housed in modular enclosures. Results are representative of a facility that achieves a net removal of 1 MtCO<sub>2</sub> per year.

The results in Figure 2 suggest a total capture and sequestration cost of \$628.85 per tonne CO<sub>2</sub> net sequestered. The largest cost contributor is the recycled PET modules, which contribute \$337.14 to the minimum product selling price. The results in Figure 2 suggest the system is capital intensive, and the total capital expenditure (shades of blue and green in Figure 2) contributes \$480.42 to the minimum product selling price. Maintenance costs are a function of the total capital expenditure and also contribute a large portion of the MPSP, \$106.22. The resulting capture and sequestration cost is heavily dependent on the CO<sub>2</sub> capture efficiency of the system. The CO<sub>2</sub> capture efficiency represents the total GHG emissions (in kg CO<sub>2</sub>-equivalence) incurred from manufacturing facility infrastructure and operating the facility long enough to sequester 1 kg of atmospheric CO<sub>2</sub> in the form of biochar. Results for the CO<sub>2</sub> capture efficiency are presented in Figure 3. The carbon capture and sequestration cost shown in Figure 2 is on par with existing DACCS technologies such as Climeworks low temperature sorbent system (with natural gas as a heat source) which achieves a capture cost of \$637 per tonne



CO<sub>2</sub> captured [5]. Furthermore, the capture and sequestration cost shown in Figure 2 include all related costs to achieve durable sequestration in the form of biochar while the costs reported by McQueen et al. [5] exclude injection of the compressed CO<sub>2</sub> stream into underground storage.

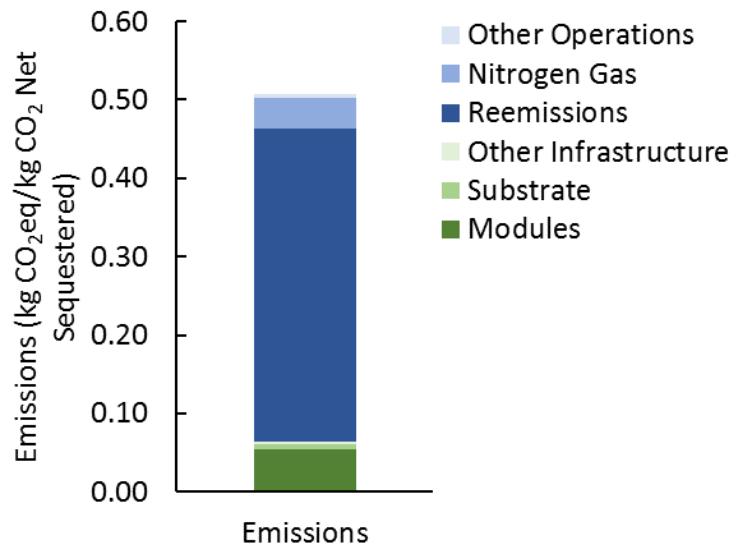


Figure 3: CO<sub>2</sub> capture efficiency utilizing the carbon capture coatings housed in modular enclosures. Results are representative of a 1 MtCO<sub>2</sub>/yr removal facility.

The results in Figure 3 suggest that for each kg of CO<sub>2</sub> captured from ambient air and converted to biochar, the system emits 0.5 kg of CO<sub>2</sub>-eq, representing a capture efficiency of 50%. Thus, the system must remove 2 tonnes of CO<sub>2</sub> to achieve the net removal of 1 tonne of CO<sub>2</sub>. The results in Figure 3 suggest reemission during pyrolysis in the form of exhaust is a key driver for the CO<sub>2</sub> capture efficiency, emitting 0.40 kg CO<sub>2</sub>-eq/kg CO<sub>2</sub> net sequestered by the system. Tailoring the pyrolysis equipment to maximize biochar could result in significant improvements to the overall CO<sub>2</sub> capture efficiency and significantly reduce capture and sequestration costs. Despite using recycled PET plastic, the manufacturing of the coating modules provides the second largest source of system emissions, emitting 0.05 kg CO<sub>2</sub>-eq/kg CO<sub>2</sub> net sequestered. Another large source of system emissions is the production of nitrogen gas used for the pyrolysis process, which results in an emission of 0.04 kg CO<sub>2</sub>-eq/kg CO<sub>2</sub> net sequestered. The use of nitrogen gas may not be necessary if an appropriate flame curtain kiln can be utilized for a slow pyrolysis process, potentially decreasing system complexity and further increasing the overall CO<sub>2</sub> capture efficiency.

## 4. Conclusion

The analysis presented here provides a preliminary techno-economic analysis and life cycle assessment of a novel algae-based carbon capture coating. The results obtained from the analysis are representative of a large-scale facility capable of sequestering 1 million tonnes of atmospheric CO<sub>2</sub> per year in the form of biochar. Results from the analysis suggest the system emits 0.5 kg CO<sub>2</sub>-eq/kg CO<sub>2</sub> sequestered (50% capture efficiency) and achieves a capture and sequestration cost of \$628.85 per tonne CO<sub>2</sub> net sequestered. The capture costs estimated with this study are on par with existing DACCS technologies including Climeworks low temperature sorbent system. Furthermore, the proposed technology offers rapid scale-up potential with the ability to utilize non-arable land and solar radiation for energy, factory line assembly of facility infrastructure, re-use of coating constituents and housings, and long periods of minimal maintenance. System economics are expected to improve significantly through engineered solutions that reduce total capital expenditure, tailor the pyrolysis process to maximize biochar formation, and maximize material recycling efficiencies within the system.

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