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Infrastructure associated emissions for renewable diesel production from microalgae

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ABSTRACT

Greenhouse gas (GHG) emissions for microalgae biofuel infrastructure are sometimes neglected during a life-cycle analysis (LCA). Construction materials were found for a baseline facility designed to produce renewable diesel in the United States. Material use was amortized over the material lifetime of thirty years and then, using emission factors available in GREET 2, energy use and GHG emissions were found per MJ of renewable diesel (MJ RD). For the baseline, infrastructure GHG emissions were 8.9 gCO_2e/MJ RD. Plastic and concrete had the largest emissions, and the growth ponds used the most materials of any unit operation. Fossil fuels comprised 97% of all energy use, which came predominately from natural gas at 0.090 MJ/MJ RD. A sensitivity analysis showed that changes to the pond liner thickness and material lifetime had the largest effects with the lifetime increasing the GHG emissions 28% over the baseline. Increasing the productivity (up to 50 g/m^2/d) or lipid content (up to 50 wt.%) decreased the emissions. Infrastructure emissions were compared to those from the fuel-cycle of a reduced emission scenario, showing that infrastructure related emissions ranged from 17% to 57% of the fuel-cycle emissions, with higher values at lower productivities.

1. Introduction

Algal biomass has received significant attention in recent years as a potential feedstock for producing renewable liquid fuels. This attention derives from expectations for large productivity when grown on marginal land that is unlikely to be used for agriculture [1]. Further, oils produced from algae, whether by extraction or by thermal conversion of the biomass to an oil product, can be converted to fuels that can be used directly in existing engines [2].

It is important to determine quantitatively whether algal biofuels reduce fossil energy use and emissions compared to petroleum fuels. Life cycle analysis (LCA) determines energy consumption and greenhouse gas (GHG) emissions associated with algal biofuel production including all upstream processes and associated activities. Upstream processes include manufacturing of nutrients and other materials as well as fossil fuel recovery to supply required electrical power and other process fuels. LCA estimates energy and GHG benefits of the algal fuel compared to the petroleum fuels that are replaced.

An LCA study must define a system boundary when examining a pathway. The system boundary defines the scope of operations to consider and its purpose is to ensure fair and sensitive comparison of alternatives. For example, if two biofuels require different feedstocks and if those feedstocks differ in energy consumption during farming, then farming operations must be included in the study to have a fair comparison.

Emissions associated with algal biofuels can be divided into the so-called fuel-cycle, infrastructure-cycle, and vehicle-cycle emissions. The majority of the emissions associated with algal fuels come from making, transporting, and burning the biofuel itself (the fuel cycle emissions), but a complete assessment should consider the emissions associated with building the algae farm and biofuel processing plants (the infrastructure cycle emissions). Similarly, the emissions associated with vehicle manufacturing (vehicle cycle) should be added. The fuel cycle, infrastructure cycle, and vehicle cycles do not overlap. Examples of infrastructure cycle items for algal biofuels include earth movement and liner material for pond construction as well as metal for various major equipment items used when harvesting and processing the algae.

Our previous LCA work [3–5] considered only the fuel cycle and neglected the infrastructure materials. This choice was made based upon the intuition that high algal productivity, a prerequisite for the algal pathway, would mitigate the effects of material usage since the material usage would be amortized over a large amount of biomass. Further, most biofuels have only small contributions from infrastructure materials. For example, farming equipment contributes less than 1% to ethanol GHGs [6]. These assumptions require deeper consideration.

This paper addresses the question of energy consumption and greenhouse gas (GHG) emissions associated with infrastructure materials required in the construction of the algae growth and processing

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plant. The work is based faithfully upon the design described in [7], henceforth referred to as the *algae baseline*. The algae baseline combined resource assessment, technoeconomic analysis, and life cycle analysis in a comprehensive model with consistent assumptions across these three modeling domains. We based the current infrastructure study on the algae baseline for three reasons. First, the model has been vetted by a number of algal researchers. Second, the model considers large scale operation, namely 19 billion liters per year (BLY) of renewable diesel. Third, the baseline design includes adequate detail to estimate infrastructure material needs for the major system components.

The remainder of this paper presents the analysis in detail, but in summary, we found that the infrastructure cycle contributed a surprisingly significant portion of the GHG emissions even when productivities higher than the conservative ones in the algae baseline were considered. The infrastructure cycle emissions derive from plastics used to line the ponds, from concrete supporting the paddlewheel mixing stations, from concrete required for anaerobic digester tanks, and from concrete used for CO_2 distribution. For the baseline design in [7], GHG emissions associated with infrastructure materials were 12% of fuel-cycle emissions. The contributions were significant even for unlined ponds, in which case they were 7.6% of the fuel cycle GHG emissions.

2. Methods

The baseline facility design was described in detail in the algae baseline report [7] and is shown schematically in Fig. 1. In brief, the design required 4050 ha of active pond area, corresponding to 1013 growth ponds, each 4-ha in size and located near the Gulf of Mexico or the Florida Atlantic Ocean coasts. The productivity at these locations averaged over an entire year was 13.2 g/m^2/day and with a lipid weight of 25%, producing approximately 19 million liters per year of raw algal oil.

Each pond was based on the design of Lundquist et al., [8] which described inoculum ponds, growth ponds, paddlewheels, and carbonation sumps. We considered both HDPE-lined ponds, per the algae baseline, and unlined ponds although unlined ponds had lined berms to prevent erosion. Initial dewatering occurred in aboveground settling tanks, followed by dissolved air flotation and, finally, centrifugation. Lipid extraction occurred via homogenization, a liquid/liquid extraction column, and centrifugation. Solvent was recovered from the oil in a stripping column. Residual biomass was sent to anaerobic digestion and the biogas was combusted in a combined heat and power (CHP) generator (gas turbine based) that was heat-integrated with the solvent recovery stripping column and with the anaerobic digesters. Materials for makeup water and a carbon dioxide distribution system were also evaluated. All infrastructure materials had an assumed lifetime of 30 years.

Information from the algae baseline [7] was supplemented with pond design data from Lundquist et al. [8], with additional details on material quantities provided by [9], which can be found in the Supplementary data section S.1. Further, [10] was used to describe the makeup water and carbon dioxide delivery systems which were not elucidated sufficiently in [7] to determine material requirements. Some operations, like dissolved air flotation (DAF), were treated via cost factors in [7] and did not have detailed construction information. In these cases, further external sources were used (details below).

CapdetWorks 2.5 [11] was a significant source of information for operations in the model that are similar to those of wastewater treatment (WWT). CapdetWorks is a computer program developed for designing wastewater treatment plants based on [12] but updated with engineering practice in 2008. Based on incoming flow rates and stream properties, CapdetWorks was used to determine a conceptual design for WWT unit operations. CapdetWorks estimated WWT associated construction materials including, e.g., concrete, steel and excavation volume. This program was used to provide conceptual designs for settling tanks, DAF, anaerobic digestion (AD), centrifugation and the pumping station for water distribution. The material requirement analysis outlined above is presented in detail in the Supplementary data associated with this article.

The total material depends upon the facility size and must be amortized over the material lifetime. To this end, infrastructure material requirements were amortized over the material service lifetime and were normalized to the total active growth area (4.11×10^7 m^2, see Supplementary data) thus giving values per square meter per day. If one then divides by a given productivity (g-algae/m^2/d), values are obtained for infrastructure materials per gram of algae. Material related emissions were then calculated from values reported in GREET 2 [13]. These emission results per mass of algae were carried forward to a fuel basis of 1 MJ of RD (our functional unit) via values from GREET utilized for the algae baseline report, namely 4.92 kg algae/kg oil and 26 g oil/MJ RD. We assumed 365 days per year when calculating the service lifetime of 10,950 days because, as it will be seen, weather-exposed materials, especially concrete and plastic, dominate the results.

3. Results and discussion

3.1. Baseline material usage

Materials for the baseline [7] were categorized according to unit operation and then summed, Table 1, which presents results in units of gram-material/m^2/day. Concrete, at 0.66 g/m^2/day, was the most used material by mass. The growth ponds used the most concrete for the paddlewheel base and the carbonation sump, but anaerobic digestion and the CO_2 delivery system contributed a significant amount as well. Cast iron had the lowest mass use at 7.37×10^{-5} g/m^2/day, which came from the pumping station in the makeup water system. The normalized excavation volume, Table 2, came almost entirely from the growth ponds.

Several elements of the infrastructure used reinforced concrete. See the Supplementary data for details. In the tables, figures, and discussions that follow, concrete is just the concrete and rebar is aggregated into the recycled steel category.

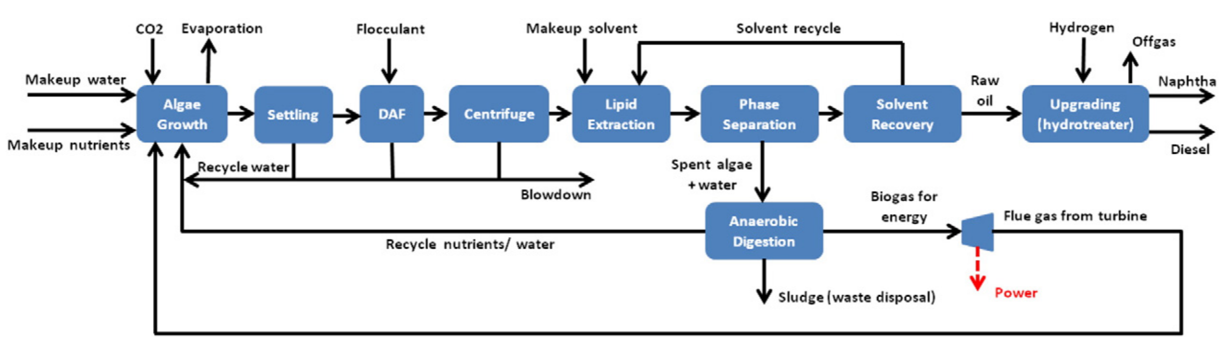

Fig. 1. Baseline scenario for the production of renewable diesel from microalgae [7].