Supporting Information (SI) for:

Environmental Performance of Algal Biofuel Technology Options

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1 Introduction and Background

The production of fuels and energy from microalgae has been investigated for over 50 years – for example, a techno-economic analysis for algae-derived electricity was published as early as 1960 by Oswald and Golueke.[1] More recently, interest in the production of liquid fuels from algae and the environmental performance of these algal biofuels has been growing. Several papers on this topic have been published in the peer-reviewed literature.[2,8,14-24] In many of these papers, life-cycle assessment (LCA) has been used to quantify environmental impacts associated with algal biofuel production. Algal biofuel LCAs are on a pond-to-wheel basis, where material and energy balances followed by an assessment of environmental releases (e.g. greenhouse gas emissions) are compiled for each life-cycle stage, including algae growth and harvesting, algal oil extraction, algal oil transport, algal oil upgrading, finished fuel transport and distribution, and vehicle use.

LCA has quickly emerged as the preeminent methodology to assess and compare the environmental performance of conventional and alternative fuel pathways.[2,24-25]. Much of the work that is currently ongoing in the external community is focused on using life-cycle principles to characterize the greenhouse gas (GHG) emissions associated with a product or process (also referred to as the ‘Carbon footprint’), though lately, interest in water consumption and its associated impacts has been growing.[12,26-29] The LCA methodology allows for the incorporation of a broad range of environmental performance indicators – global warming, acidification and eutrophication to name just a few, see Figure S1. Further details pertaining to the various phases of a typical LCA study and the broad ISO (International Organization for Standardization) guidelines that exist to conduct these studies are available elsewhere.[30-31]

Subsets of LCA are also very common – an example is a Well-to-Wheel (WTW) analysis for ground transportation fuels or a Well-to-Wake (also WTW) analysis for aviation fuels. A WTW assessment is usually conducted in two stages: Well-to-Tank or Well-to-Pump (fuel production) and Tank-to-Wheel or Pump-to-Wheel (fuel combustion / use). Models to investigate the WTW performance of fuel-vehicle systems exist – these include GREET and GHGenius, among others.[32-33] In the present work, we have chosen to use the GREET platform (Version 1.8b) to study the environmental performance of algal biofuels. GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) is a multi-dimensional spreadsheet model developed by Argonne National Laboratory (ANL). It is the preferred WTW platform of U.S. regulatory agencies and is currently being used to support regulatory and policy decision making.[25, 34] For example, the California Air Resources Board (CARB) uses a modified version of the GREET model to assess the carbon intensity of different fuel and energy pathways.[34] GREET is also extensively used in industry studies and by academia.[35]

The GREET model has over 70 predefined fuel-vehicle pathways that can be assessed in a relatively straightforward fashion – once key inputs, such as process efficiencies, and scenario options have been specified, the model generates GHG and energy use estimates on a WTW basis. When the current research was conducted, the GREET model did not include pathways for algae-derived fuels, though these are currently being developed by ANL.[36] Incorporating new algae pathways in GREET requires developing a process model for the production of algal biofuel that contains adequate detail to characterize different technology approaches and their underlying parameters. We have developed a process model based on publicly available information and the collective engineering judgment of the authors. Using this process model, energy and freshwater consumed in algal biofuel production are estimated. This data is then used within the GREET framework, Version 1.8b, to calculate life-cycle GHG emissions and energy use. The LCA calculations draw on information generated by the process model and data that is already available in GREET (e.g., life-cycle GHG emissions associated with electricity production and transmission). A detailed description of GREET and the model files is available elsewhere,[32] while a description of the process models developed in this work is in an ensuing section of this write-up. Issues pertaining to scale-up, systems integration and cost are not addressed in this study – as noted in the main paper, the ultimate viability and sustainability of algal biofuels will also be governed by these factors.

1.1 Recent studies on algae environmental performance

Several LCA studies on algae have recently been published in the peer-reviewed literature.[2,14-24] Table S1 compares and contrasts a subset of the published work on algae environmental performance. It is clear from the table that many technology and parameter options exist for algae processing. There is value in exploring these options using LCA. In other words, LCA could be applied as a system level tool for 'trade space' exploration, where the system constitutes all the elements in the algal biofuel production chain. We define 'trade space' as the set of technology options that are available for algal biofuel production. However, to enable this kind of an analysis, a consistent set of assumptions regarding the system and the methodology needs to be made, which is what the current work attempts to do. As highlighted in the main article, the goal is to understand how various technology options affect life-cycle greenhouse gas emissions (GHG) and on-site freshwater consumption, and to develop principles that can guide R&D to enable the development of facilities with both low GHG and freshwater consumption.

2 GIS analysis

Regional site selection for algal biofuel production has been addressed qualitatively with a GIS software package and publicly available data for solar insolation, local climate, and CO_2 sources. The results are presented in Figure 1 of the main paper. Data sources used to develop the analysis are presented in this section.

The 10 km average annual global horizontal solar insolation data set from NREL has been used.[37] This data set shows considerable variation of solar insolation across the country from east to west coast, but limited differentiation between northern and southern states. Using this metric alone would indicate that both Wisconsin and Texas are equally suited for photosynthetic algae production. To correct for differences in growing conditions, the annual average number of frost-free days[38] is used to account for winter temperatures that can have a material effect on the length of the growing season. In this case, a threshold of greater than 6 months of frost-free climate is used as a lower bound for identifying locations to site the notional facility modeled in this work. NOAA data with number of days with 90% probability of having temperatures greater than 273 K has been used in the analysis.[38] Finally, the location and capacity of coal-fired power plants is based on data from the Energy Information Agency.[39] Coal plants have been chosen for their relatively high flue gas CO_2 concentration,[40] and only operating coal-fired power plants, with generation capacity of at least 250MW are considered in this analysis. Brackish surface and ground water availability has not been included due to a lack of information in the literature.

3 Algal biofuel production system

3.1 Pond layout and algal biofuel technology options

The algae are grown in paddlewheel-mixed, open raceway ponds.[3,4] Ponds of this type have been utilized for commercial algal biomass production.[3] We assume the facility has a fixed total pond area of 400 ha, with 40 growth ponds of 10 ha each. Pond grade is established via rough grading and laser leveling. The surface of each pond may be lined with a thin layer of clay or with a plastic liner. A pond depth of 30 cm and mixing velocity of 20 cm/sec are used based on estimates that have been reported in the literature. The pond areas assumed in this study are larger than what has been demonstrated in long-term outdoor studies. The layout of our pond system is shown in Figure S2.

The power that is required to mix the ponds is estimated using Manning’s formula[4] for flow in open channels. The head loss is first calculated – it is a function of the depth of the pond, the Manning friction coefficient, the mixing velocity and the total channel length. The Manning friction coefficient is assumed to be 0.023 in the present work, though it can range from 0.010 to 0.029 depending on the nature of the inner surface of the ponds.[4] The head loss is used to determine the power required to mix the ponds. An overall pond mixing efficiency of 42% is assumed in the calculation, though this parameter is varied in the sensitivity analyses described in the main paper and later in this report. The overall efficiency is a function of the hydraulic efficiency of the paddlewheel and the drive system that is used.[4]

All results presented herein are specific to the layout shown in Figure S2; however, as pointed out in the main paper, the qualitative trends presented may be more broadly applicable. In addition to the growth ponds, a separate facility with closed bioreactors is used to produce the inoculum that is used for seeding. The water in the growth ponds is assumed to be either saline or brackish. Make-up water is pumped to the ponds to compensate for pond evaporation and blowdown, and to maintain the desired salinity. Two carbonation stations with sumps are used in each growth pond to deliver CO_2 to the algae. The design of the carbonation stations is based on literature data.[3,4]

The ponds are assumed to have a steady state algal biomass concentration of 0.02-0.05 wt% (ash free dry weight). Therefore, a dilute biomass stream is harvested from the ponds. As noted in the paper, the solids content of the harvested stream is increased via multiple thickening and dewatering steps. Dewatering facilitates recovery of algal oil from the biomass in the dry and wet extraction technology sets, and further processing of the residual biomass in the secretion technology set. The harvesting stages concentrate the pond outflow to 12-18 wt% solids.

In the dry extraction technology set, algal oil in the form of triacylglycerides (TAGs) is recovered from the biomass using hexane solvent extraction. Hexane extraction is commercial technology that is used at scale to recover soy oil from soybeans.[41] However, as described in the main paper, barriers to implementation exist as hexane solvent extraction has not been commercially demonstrated with algal biomass. To enable algal oil recovery with hexane, the algal cells need to be lysed. This allows access to the oil. Also, intra-cellular water has to be removed to prevent emulsion formation during the solvent extraction process. We use a belt drying system, modeled after commercially available sludge belt dryers,[42] to both lyse the algal cells and dewater the algae to ~90 wt% solids. We have suitably adapted the energy inputs associated with the hexane solvent extraction process for soybeans[41] so as to be applicable for algae.

An alternative extraction approach is to recover the oil from ‘wet’ biomass. Wet extraction techniques are at a nascent stage of development, but have been assessed using the limited information available in the public domain,[6,43-45] supplemented with in-house modeling results. The benefit of wet extraction is that it eliminates the need for a drying system. We have modeled a wet extraction scheme based on literature data.[6,43] Here, the concentrated stream from the dewatering steps (~12 wt% solids), is lysed with steam and KOH. Oil is recovered from the broth using a series of centrifugations and wash cycles. Energy inputs assumed in the wet extraction step to yield the results shown in Figures 3 and 4 of the main paper are based on literature estimates,[43] additional details are in an ensuing section.

Secretion of oil from algae biomass has been demonstrated externally.[7] In the secretion technology set, the algal oil in the form of free fatty acids is secreted by the algae into the ponds. Evaporative losses of the oil from the pond surface are accounted for in the modeling.[46] An alternative is to use covered ponds, however cost trade-offs would then need to be assessed. An added benefit of using covered ponds would be the reduction of evaporative water losses. The oil is recovered from the pond surface using a skimmer (e.g. slotted pipe). The drying and solvent extraction steps, which are integral to the extraction technology sets, are no longer required. Residual biomass still needs to be harvested from the ponds to maintain oil productivity and remove dead matter. As described in the main text, several significant challenges need to be overcome to make secretion a viable oil recovery option.

Once the algal oil has been recovered, it is transported to a refinery and upgraded using hydroprocessing techniques that are well established in industry. Data inputs for the hydroprocessing of TAGs are taken from the literature.[47-48] For the hydroprocessing of free fatty acids, the product slate and algal biofuel yields are adjusted because propane is no longer formed. Upgrading energy burdens are expected to be similar to TAGs.

Multiple residual biomass utilization methods are considered, post-oil extraction. The residual biomass may be sent to a two-stage anaerobic digester to produce biogas.[49] The biogas is burnt on-site to generate heat and/or electricity. If electricity is generated from the biogas, we use generation efficiencies from the literature.[50] CO_2 produced in digestion and biogas combustion is recycled back to the growth ponds and used for algae growth. This implies that there are two CO_2 feed streams to the pond system: (a) the recycle stream from the biogas burner, and (b) make-up or fresh CO_2 that is externally sourced. The presence of the recycle stream reduces the amount of make-up CO_2 needed for algae growth. If CO_2 must be captured from the combustor flue gas stream, a Mono Ethanol Amine (MEA) scrubber is assumed, with operating variables taken from ref. 51 and an assumed CO_2 capture efficiency of 90%. The concentrated recycle CO_2 stream is compressed to ~20 bar before it is distributed and fed to the algae growth ponds – parameters for the compressor are based on literature estimates.[52] For flue gas feed to the ponds, we estimate a compression energy debit of ~28 kJ/kg-flue gas – this assumes that relatively large ducts are used to deliver and distribute the flue gas streams in the facility. The effluent stream from the digester is pumped back to the ponds – the nutrients in this stream are recycled and reused for algae growth. Another disposition option considered is the sale of the residual biomass as feed. To the extent this path is utilized, it precludes the possibility of nutrient recycle for algae growth, and also eliminates internal CO_2 recycle. Make-up CO_2 and nutrient inputs to the growth ponds are therefore higher when compared to the case where the residual biomass is digested.

3.2 Overview of calculation approach

Our calculation methodology is summarized in Figure S3. This chart applies for the dry and wet extraction technology sets. A similar approach is used for secretion. In the model, the algae productivity and the concentration of algae biomass in the ponds are specified as inputs. With this information and the total pond area (400 ha), the culture harvest rate is calculated. The harvest rate and the total culture volume are used to determine the pond dilution rate and detention time. A validity check is then performed to ensure that the dilution rate and the detention time are consistent with values that have been reported in the literature. The biomass harvesting (dewatering) units are sized based on the harvest rate, and the energy burden associated with their operation is estimated using vendor-supplied and publicly available data. In parallel, we estimate on-site (direct) freshwater consumption associated with algal oil production (not shown in Figure S3). The calculated energy burdens and material flows are used as inputs to the LCA calculations that are performed in GREET 1.8b.

4 Nominal extraction and secretion technology sets

The objective of this study is to assess a range of process technology and scenario options for algal biofuel production. To facilitate this analysis, nominal technology sets need to be defined for the three oil recovery options assessed (dry and wet extraction, and secretion). Note that the nominal technology sets are not optimal, and only serve as reference cases for the scenario and sensitivity analyses performed herein. Simplified process flow diagrams (that highlight carbon and water flows) for all three nominal technology sets are shown in Figure 2 of the main paper. Note that the carbon flows shown in the figure assume 100% biomass recovery in the harvesting units, an assumption that is relaxed in the life-cycle energy and GHG calculations.

4.1 Nominal dry and wet extraction technology sets

The composition of the algal biomass assumed in the nominal dry and wet extraction technology sets is shown in Table S2. Weight (and carbon fractions) and lower heating values (LHVs) for the various constituents of the biomass (protein, carbohydrate, and lipid) are based on literature data.[53-59] The lipids that are recovered from the algae are in the form of triacylglycerides (TAGs), and are upgraded to diesel range molecules in a hydroprocessing unit.[47-48]

Key assumptions pertaining to algae growth and the pond system, along with the data sources used are summarized in Table S3. We have assumed an average annual algae productivity of 20 grams/m^2/day (ash free dry weight basis; per unit pond area). A productivity of 20 g/m^2/day is at the high end of what has been demonstrated in the past in long-term outdoor studies, but is considered to represent a reasonable starting point for a near-to-mid term technology target. We assume an overall lipid extraction efficiency of ~70% in the nominal dry extraction tech set (i.e., 70% of the lipids in the algae biomass are recovered and upgraded to algal diesel). This estimate is also at the high end of what has previously been demonstrated, but represents a reasonable near-to-mid term technology target (e.g., ref. 9). For wet extraction, similar oil productivities are assumed to enable consistent comparisons with dry extraction.

The algae are grown in saline, paddlewheel mixed, open raceway ponds. The concentration of biomass in the ponds is assumed to be 300 parts-per-million (ppm), which leads to a pond detention time of about 4.7 days, in the range of what has been reported in the literature.[4] An evaporation rate of 0.5 cm/day is chosen, representative of evaporation rates that are expected in non-arid regions of the U.S. Make-up water is brackish, with total dissolved solids (TDS) of 20 parts per thousand (ppt). The make-up brackish water is pumped over a distance of 8 km (5 miles). To maintain a steady state TDS of 40 ppt in the ponds, a blowdown ratio of 1 is required (i.e., blowdown equals evaporation). Each growth pond in the facility is cleaned three times every year. During turnaround, the discharge from the ponds is treated in a conventional municipal wastewater treatment facility, and is either disposed or reused. The energy and GHG burdens associated with wastewater treatment are taken from ref. 65. Additional details on the water assessments performed in this study are available in Section 9.

The total carbon input required for algae growth is calculated using the assumed biomass composition and representative carbon fractions for the various constituents of the biomass. Based on literature estimates,[4] a carbon utilization (absorption) efficiency of 90% is used for the ponds, which means that 90% of the CO_2 fed to the ponds is fixed in the algae, while the remainder is outgassed to the atmosphere. In the nominal extraction technology sets, there are two CO_2 feed streams to the algae ponds – recycle CO_2 from the biogas (and natural gas) burner(s) and make-up CO_2 from an external source; in this work, the external source is assumed to be a coal-fired power plant. The coal power plant and the algae facility are nominally co-located (8 km distance) and flue gas is fed to the ponds using sumps.[3] The flue gas stream has ~20 wt% (13 mole %) CO_2, which is representative of flue gas produced in a pulverized coal power plant.[40] The design of carbonation stations for flue gas and pure CO_2 (if used) are based on refs. 3 and 4.

Nutrient inputs have been determined using Redfield ratios, assuming a seawater culture. The life-cycle burdens that are incurred in the production of these nutrients are calculated using the GREET model and the Ecoinvent database.[65] The average nitrogen fertilizer mix used in the U.S. is assumed as 70.7% ammonia, 21.1% urea, and 8.2% ammonium nitrate (also includes ammonium sulfate and ammonium thiosulfate). GREET 1.8b estimates phosphate fertilizer burdens using phosphoric acid data. Iron is supplied to the ponds in the form of $FeSO_4$, with life-cycle data taken from Ecoinvent.[65] A nutrient use efficiency of 90% is assumed, with small losses attributed to medium losses during harvest or culture kills. A nominal nutrient recycle efficiency of 60% is chosen for the anaerobic digester, based on Weissman and Goebel.[4]

In the nominal extraction technology cases, algae biomass is harvested using dissolved air flotation (DAF) and centrifuge separation. For the harvesting units, the two-stage anaerobic digester, the belt drying system, the oil extraction unit and the hydroprocessing unit, operating variables have been estimated using vendor inputs and literature data; see Tables S5-S8 for further details. Note that natural gas is required in the nominal dry extraction case for biomass drying. A total of nine DAFs running in parallel and one centrifuge is required in the nominal dry extraction technology set – the number of harvesting units depends on the total flow rate that has to be handled and unit capacity. For the anaerobic digester, we assume that the inflow has to have a biomass content of 12-15 wt%. This implies that in the nominal dry extraction technology set, water has to be added to the residual biomass stream (post oil extraction) before it is fed to the digester. The volume of biogas produced is calculated as the product of digester efficiency, biomass flow rate into the digester and biogas yield. Parameters such as pipeline pressure drop and overall pumping efficiency are based on literature data and our own engineering judgment. The pressure drop and the overall pumping efficiency are used to calculate the power required to move liquids in the facility. To move streams that have a high solid content (e.g. the concentrated outflow from the DAF to the inlet of the centrifuge), either specialized slurry pumps or conveyor belts are used, using vendor-supplied energy data. Operating variables and energy inputs for the primary (DAF) and secondary (decanter centrifuge) harvesting units are shown in Table S6. Other harvesting options have been explored in this study and are described in Section 7.

Biogas (65 vol% CH_4 and 35 vol% CO_2) produced in the anaerobic digester is combusted to generate heat in the dry extraction technology set. We assume that ~20% of the heat is used in the digester, while the remainder is used in the biomass drying step. Electricity is produced with an assumed efficiency of ~35%[50] from the biogas in the wet extraction technology set. Electricity is generated instead of heat because there isn’t a significant thermal demand on-site for wet extraction. See Section 6 for additional details on the energy flows in algal oil production.

Energy and hydrogen inputs for the upgrading step are taken from the literature[47-48] and are presented in Table S8. Hydrogen is produced from natural gas via steam reforming.

4.2 Nominal secretion technology set

We consider a specific manifestation of secretion to enable comparisons with the nominal extraction technology sets. Instead of defining an overall algae productivity and a recoverable oil fraction (as was done for dry and wet extraction), we defined separate productivities for the secreted oil and the residual biomass that is harvested from the ponds. We assume a secreted oil productivity of 5 $g/m^2/day$ and a residual biomass productivity (excludes the secreted oil fraction) of 15 $g/m^2/day$. This is consistent with the nominal dry extraction technology set, which has an overall algae productivity of 20 $g/m^2/day$ and a recoverable oil content of 25%. In the extraction model, the biomass residue that remains after oil extraction has ~13% lipids (oil fraction that is not recovered), ~60% proteins and ~27% carbohydrates. We use these same weight fractions in the harvested residual biomass stream in the secretion technology set. Identical dilution rates (or pond detention times) are assumed for both secretion and extraction. Therefore, the steady state concentration of residual biomass in the ponds for the nominal secretion case is 225 ppm, versus 300 ppm of total biomass in the nominal extraction technology set. This ensures that the photosynthetic efficiencies for the two models are roughly equivalent and the ensuing comparisons are consistent. The secreted oil is assumed to be in the form of free fatty acids.

Key assumptions and inputs for the nominal secretion technology set are shown in Table S9. In the skimming system, we recover 10 L of water for every L of oil skimmed from the pond surface. The water is separated from the oil in an oil/water separator and pumped back to the ponds. Low shear pumps with an assumed efficiency of ~50% are used to pump the oil-water mix. Motors needed to run the skimmer are chosen based on technologies that are commercially used today for wastewater treatment. Though this is a reasonable approach, it is unclear whether the secreted algal oil can be skimmed in the manner assumed in this study. Significant research and development is needed to this end.

The secreted fatty acids are, as before, upgraded in a hydroprocessing unit to diesel range molecules. We assumed that the energy burdens in the upgrader are similar to TAG hydroprocessing. However, the product slate and the fuel yield were adjusted because propane is not formed in fatty acid hydrogenation. Instead of the ~85 kg of diesel per 100 kg of feed produced in TAG upgrading, ~89 kg of diesel per 100 kg of feed is produced when fatty acids are upgraded. As mentioned in the main paper, metallurgy and the engineering / design of the reactor used in the upgrading step would likely be different to account for corrosion and fouling related considerations – these are not within the scope of the present analysis. As in the nominal wet extraction technology set, biogas is produced from the digestion of the residual biomass and used to generate electricity. The inputs, assumptions and operating variables for the other process units, (e.g., DAF, centrifuge, and anaerobic digester), in the system are unchanged from the nominal extraction case (see Tables S5-S8).

The nominal secretion technology set considered here is not ideal from the standpoint of liquid fuels production as a significant amount of biomass is harvested from the ponds. Since the intent was to carry out a consistent comparison with nominal extraction, the assumed residual biomass and secreted oil productivities are reasonable. A preferred manifestation would be one where most of the incoming solar radiation is utilized to make oil, which is subsequently secreted, with little biomass being harvested.[23,68]

5 Functional unit and co-product valuation

The functional unit we have chosen is 1 MJ of fuel energy (LHV-basis) for the life-cycle GHG calculations. For direct freshwater consumption, results are presented in liters per liter of oil equivalent energy. The latter captures differences in energy density between the various fuel options compared in this study.

Co-product valuation can have a significant impact on environmental performance.[2,24,47] To avoid the value judgments associated with co-product treatment, we have attempted to keep co-product formation to a minimum. As an example, all the biogas that is produced in the anaerobic digester is burned to generate either heat or power. The heat is used to dry the algae biomass in the dry extraction technology cases. The power is used on-site in the harvesting units, to move liquids around the facility and to mix the growth ponds. If the thermal load for the system is small, which is the case for the wet extraction and secretion technology sets, the biogas is converted to electricity and used on-site. In some of the scenarios modeled, there may be some surplus electricity available after internal demands have been met. This surplus power is exported to the grid. A ‘system expansion’ approach is assumed, whereby the electricity ‘displaces’ a U.S. grid average electricity mix (an alternative would be to displace the marginal resource in the mix). Environmental impacts that are ‘avoided’ as a consequence are taken as a credit against the primary product (algal diesel). The environmental footprint of the grid mix is based on GREET 1.8b defaults.[32] This approach is consistent with ISO recommendations[30] and is also the methodology that is currently used by the Environmental Protection Agency (EPA) in the EISA RFS2 LCA calculations.[25] The electricity production is small relative to the energy contained in the diesel fuel being produced, so the impact will not distort the results; this is not always the case as has been reported by ref. 2.

Alternate co-product disposition and valuation schemes have been considered as a part of the parameter and scenario assessments performed in this study. For example, the use of residual biomass as animal feed was considered – as mentioned in the main text, a system expansion approach was used to value the co-product, analogous to ref. 8. Residual biomass ‘displaces’ soybeans based on protein equivalency. The avoided life-cycle GHG burdens (associated with soybean cultivation) are attributed as a credit to algal diesel.

6 Energy balance

6.1 *Energy flows in algal oil production*

Our intent, in this section, is to compare the amount of energy required to produce algal oil with the amount of energy that is contained in the oil that is produced, and supplement the discussion on energy flows in the main paper. Only fossil energy inputs are considered here, and the energy in the algal oil is represented on a LHV basis. In the figures that follow (Figures S4 and S5), we do not distinguish between different energy forms, e.g. electricity and natural gas, so energy ‘quality’ is not accounted for and all energy types are treated equivalently. Also, we do not include the energy burdens associated with the upgrading step and instead focus only on algal oil production.

Figure S4 shows the energy flows in the nominal dry and wet extraction technology sets. Positive numbers represent energy outflows, while negative numbers represent energy inflows. It is evident from the figure that in the nominal dry extraction technology set, much of the energy burden is in biomass drying.

Energy consumption in the wet extraction step is primarily associated with the steam that is required to lyse the wet biomass; here, we have used external estimates for steam consumption based on ref. 43. Since wet extraction is nascent technology which is still under development, there is uncertainty in the energy inputs associated with the process. As mentioned in the main paper, in-house calculations using a simple process model (heat integration was not considered, hence the estimate is likely on the high side) suggest a higher steam demand for wet extraction (~0.7 kg/kg-algae) than reported externally; however, the energy balance for the nominal wet extraction technology set remains favorable with the higher steam requirement assumption.

As pointed out in the main paper and in an earlier section of this document, the utilization of biogas that is produced via anaerobic digestion of the residual biomass differs in the dry and wet extraction technology sets. In dry extraction, the biogas is combusted to exclusively produce heat that is used in the biomass drying step. This energy is included in the biomass drying category shown in Figure S4. On the other hand, in wet extraction, electricity is produced from the biogas. This electricity is completely consumed on-site and offsets a portion of the electricity burdens associated with algae growth, flue gas distribution, harvesting and wet extraction. In other words, in wet extraction, electricity is produced from biogas and this reduces the net electricity input to the system.

Even though there is a large energy debit associated with drying, there are situations where the energy balance for dry extraction is favorable. Figure S5 shows the energy inputs and outputs per kilogram of algae biomass for the low-impact, nominal and high-impact dry extraction cases, as defined in Table 1 of the main paper.

As can be deduced from Figure S5, the low-impact dry extraction technology set has a favorable energy balance. Since a higher recoverable oil fraction is assumed, per kg of algal biomass grown, more oil is produced in the low-impact case (versus the nominal). Furthermore, in the low-impact case, the use of more efficient harvesting technologies lowers the energy burden in the harvesting step and also indirectly reduces the amount of energy that is used for drying. A smaller amount of water needs to be evaporated by virtue of the higher solids content in the dewatered stream that is fed to the belt dryer. On the other hand, in the high-impact case, per kg of algae biomass, there is less energy in the algal oil. Also, CO_2 supply is a major contributor to the energy burden because CO_2

(both recycle and make-up) has to be captured from a dilute flue gas stream using an energy-intensive scrubber in the high-impact case.

The energy flows associated with the low-impact, nominal and high-impact secretion and wet extraction technology cases (not shown) can be generated in a similar fashion. The low-impact and nominal cases have a favorable energy balance, while the high-impact case does not.

6.2 Cumulative energy demand for nominal dry & wet extraction

Cumulative energy demand (CED) for algal diesel production is estimated using GREET 1.8b[32] and does not include solar energy. Energy required to upgrade the algal oil to diesel is included in the CED calculations. Based on GREET, we assume that a total of ~2.3 MJ of fossil energy is required over the entire fuel-cycle to produce 1 MJ of U.S. grid average electricity, while ~1.07 MJ of fossil energy is required to produce 1 MJ of natural gas (LHV basis).

The wet extraction estimates for NER and CED in the main paper assume literature data for the steam that is required in the wet extraction step. As pointed out previously, there is uncertainty in these inputs. Using a steam burden determined in-house with a simple process model yields a lower NER value of ~2 for the nominal wet extraction technology set.

7 Parameter and scenario analyses

In a similar fashion to Figure 3 of the main paper, the GHG performance of the nominal extraction and secretion technology sets is presented in Figure S6. Changes in GHG due to the modification of selected process technologies and parameter values within the nominal secretion case are also shown. These sensitivities are used both to identify variables with a strong influence on GHG and to develop bounding low and high-impact cases. The varied parameters and processes may be broadly categorized as productivity, siting and engineering, pond inputs, harvesting process selection, and biomass disposition.

The trends observed in the secretion sensitivity analysis are predominantly the same as those identified in the discussion of dry extraction in the main text, with a few noticeable exceptions. The first is the overall reduction in the magnitude of the emissions; this causes the sensitivities to be larger relative to the nominal secretion baseline. Additionally, this causes a greatly reduced impact of changing oil productivity. Recall that the influence of oil productivity is multiplicative with the cumulative emissions from cultivation and harvesting; hence, reducing the emissions from cultivation and harvesting (primarily due to absence of drying) reduces the sensitivity to algal oil content (represented here as a secreted oil productivity). The second is the elimination of emissions from drying, which manifests in the form of a greatly reduced impact of implementing a more efficient secondary harvesting unit (a disc centrifuge with a higher effluent biomass concentration). And finally, the impact on GHG of using residual biomass as feed is very dependent on whether the biomass needs to be dried before it is used for this purpose. Also, as noted in the main text, co-product allocation methodology and carbon accounting become important considerations when the residual biomass is not utilized internally.

The important differences between the nominal technology set and the bounding cases for secretion are summarized in Table S10. This follows the definition of the dry extraction bounding cases in Table 1 of the main text.

In the low-impact secretion case, we chose an oil productivity that is comparable to the oil productivity used in the low-impact extraction cases (~75 m^3/ha/year). However, we assumed that less residual biomass is produced in the low-impact secretion case vs. the low-impact extraction cases. This is equivalent to assuming a longer detention time for the residual biomass that is harvested from the ponds, ~22.3 days. Still longer detention times[23] and higher oil productivities might be possible[68] with a secretion model; however these scenarios are not considered in this work.

A sensitivity analysis has also been conducted for wet extraction. The observed trends are, in general, similar to secretion. The bounding technology cases are defined as described previously for dry extraction and secretion. As noted in the main manuscript, with a higher steam requirement of ~0.7 kg/kg-algae (Table S5) in the wet extraction step, pond-to-wheel GHG for the low-impact, nominal and high-impact cases are 5, 72, 416 grams-CO_2 eq./MJ, respectively.

8 Materials of construction and infrastructure

It has been reported in the literature that the GHG impacts associated with the manufacture of pumps, paddlewheels and centrifuges is small relative to the magnitude of the other life-cycle stages in an algae production system.[19] Here, we have estimated life-cycle GHG for the manufacture of liners that may need to be used in the growth ponds. As mentioned in an earlier section, there are multiple options available to line the ponds: crushed rock, clay, and plastic sheets. We considered a scenario where plastic is used and assume high-density polyethylene (HDPE). From a GHG perspective, the use of a plastic liner is expected to have the largest impact and therefore represents a possible upper-bound. The area of the plastic liner is taken to be equal to the pond surface area, with a small additional amount to properly anchor the liner. The carbon footprint for the manufacture of a kg of HDPE is taken from the Ecoinvent database.[65] The GHG impact of the pond liner depends on the life and the thickness of the liner. Not surprisingly, higher biomass and oil productivity levels lead to a smaller emissions impact. For the low-impact, nominal, and high-impact dry extraction technology sets, life-cycle GHG associated with the manufacture of the pond liner, with thickness of 0.15 cm (60 mil) and an assumed service life of 10 years, are: 1.4, 5.3, and 11.7 grams-CO_2/MJ-algal diesel, respectively. These represent ~2% (or less) of the total pond-to-wheel GHG emissions impact calculated for these three technology cases. The contribution, as a fraction, is larger in the wet extraction and secretion cases because the overall pond-to-wheel GHG impacts are lower than dry extraction. For nominal wet extraction and secretion, pond liner manufacture contributes almost 10% of the total life-cycle GHG impact. In the analysis, we have not included the burdens associated with the installation of the liner and other infrastructure elements in the facility as these are expected to be small.

9 Direct (on-site) freshwater consumption

9.1 Terminology

In addition to life-cycle carbon emissions, it is essential to analyze the performance of algal biofuels along other environmental dimensions. To this end, we conducted an assessment of direct freshwater consumption for algal biofuel production. It is useful to define and clarify some important terms that pertain to the freshwater calculations.

Water consumption vs. withdrawal:

- Consumption: water is removed from a source (such as an aquifer) and not returned directly to that source,[26,27] (e.g. evaporative losses in a closed-loop cooling system for power generation)
- Withdrawal: water is used and returned to the source[26,27], (e.g. water is withdrawn and then returned to the source in an open-loop cooling system for power generation)
- In the present work, we model freshwater consumption

Direct (on-site) vs. indirect consumption

- Direct: consumptive water use ‘on-site’, e.g. evaporative losses on-site in the algal oil production facility
- Indirect: consumptive water use ‘off-site’, e.g. water consumed in generating power or natural gas that is imported for use in the algal oil production facility
- In this study, we have focused on direct freshwater consumption. Note that the terms direct and on-site have been used interchangeably in this write-up.

Fresh vs. brackish vs. saline water: total dissolved solids (TDS)

‘Total dissolved solids’ (TDS) is a measure of the organic and inorganic content of a liquid in suspended or molecular or ionized form. It can be used as a broad indicator of water quality and salinity. TDS levels for the water categories that are pertinent to the present work are loosely defined as shown below,[69] where ppt is parts per thousand:

- sea water: 28-40 ppt
- brackish water: 1–28 ppt
- fresh water: < 1 ppt

9.2 Key inputs and assumptions for algal biofuel freshwater analysis

Key data inputs and assumptions used to calculate the direct freshwater consumption ranges shown in the paper are summarized in Table S12. All calculations reported in this section are for the dry extraction technology sets and results are reported for the low-impact, nominal and high-impact cases. Note that productivities for the bounding technology cases are defined as described in an earlier section of this write-up and in

Table 1 of the main paper. Scenarios with fresh and brackish make-up to the ponds are considered separately.

An evaporation rate of ~0.5 cm/day was used for the results presented in Figure 5 of the paper, based on pan evaporation data that is available externally (e.g. see ref. 72). This is considered to represent a conservative estimate for portions of the U.S. southeast (e.g. Texas). However, it should be noted that pan evaporation rate data show significant regional variations[3] across the continental U.S., and the actual evaporation rate will depend on where the algae facility is sited. The blowdown ratio is chosen based on the nature of the make-up water to the ponds. It is a multiplicative factor that is used to determine the blowdown rate required to avoid salt build-up and maintain a desired salinity level. In other words, the rate of blowdown is the product of the evaporation rate and the blowdown ratio. Make-up compensates for all losses from the pond i.e. make-up rate = evaporation rate + blowdown rate + photosynthetic loss. The steady state TDS in the ponds is calculated using the TDS of the make-up water stream and the flow rates of the make-up and blowdown streams.

9.3 Freshwater consumption estimates for other fuels

In the paper, we have reported freshwater consumption ranges for corn ethanol, soy biodiesel and petroleum-derived gasoline to enable comparisons with algal diesel fuel (see Figure 5 of the paper). These ranges are based on literature estimates and include freshwater consumption for both feedstock and fuel production (Table S13).

For the biofuel pathways, the ranges are governed primarily by whether the feedstock is irrigated during cultivation and by regional irrigation water requirements. In estimating freshwater consumption during cultivation for corn ethanol, we have considered water consumption factors across the US.[73] To account for differences in energy density for the fuels being compared, we have reported freshwater consumption in liters per liter of oil equivalent energy (Figure 5 in the main paper). In converting to these units, we used fuel product energy densities from GREET 1.8b,[32] and assumed that a barrel of crude oil (159 L-oil) has 5.74 GJ of energy on a lower heating value basis.

10 Direct land use considerations

We have assumed that the algal oil production facility is sited on degraded land. Consequently, GHG emissions associated with direct land use change are either small or negligible, and are therefore not included in the pond-to-wheel GHG estimates shown in Figure 4 of the main paper. To explore the potential impact of land conversion, as an upper bound, we consider a scenario where grasslands are displaced.

The total growth pond area assumed in this work is 400 ha (see Section 3). Including the land required for biomass harvesting, algal oil extraction and residual biomass processing, we estimate a total area of ~450 ha for the algal oil production facility considered here. We assume that the biomass (both above and below ground) and soil carbon contents for grasslands in the U.S. are 10 and 80 tonnes-C/ha,[74] respectively. If all the biomass carbon and 25% of the soil carbon are converted to CO_2, direct land use change emissions work out to be less than 2% of total pond-to-wheel GHG in the nominal dry extraction technology set, or ~5 grams-CO_2/MJ-algal diesel. In the calculation, we assume that the facility has a life of 40 years, and land use change emissions are amortized over the life of the facility. Avoided carbon sequestration credits are not included. Higher oil productivity levels lead to a large reduction in direct land use change GHG – e.g., in the low-impact dry extraction technology set, grassland conversion results in direct land use change emissions of ~1 gram-CO_2/MJ, using the calculation approach described above. For degraded lands, emissions associated with land conversion are still smaller, because degraded lands have very little living biomass; e.g., a biomass carbon content of 1 tonne-C/ha is assumed in ref. 75 for degraded lands (vs. 10 tonnes-C/ha for U.S. grasslands). The analysis suggests that if degraded lands are used and/or oil productivity targets are met, direct land use change emissions are insignificant for algal biofuel production.

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Supporting Figures

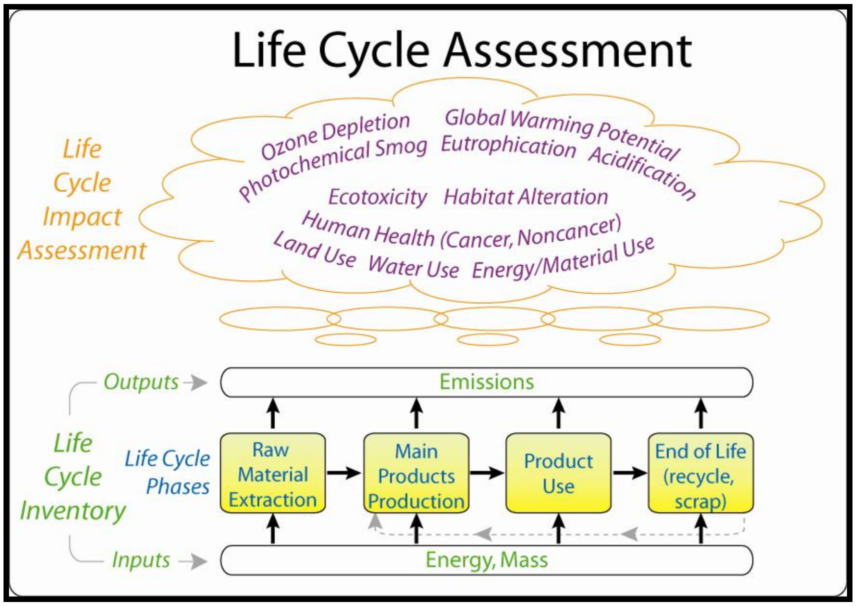


Figure S1: Life-cycle assessment framework for a generic product. Two of the key stages of LCA are shown – life-cycle inventory (LCI) and life-cycle impact assessment (LCIA). In LCI, material, energy and environmental flows are compiled for each life-cycle stage. In LCIA, the impacts of environmental releases, such as GHG, are assessed.

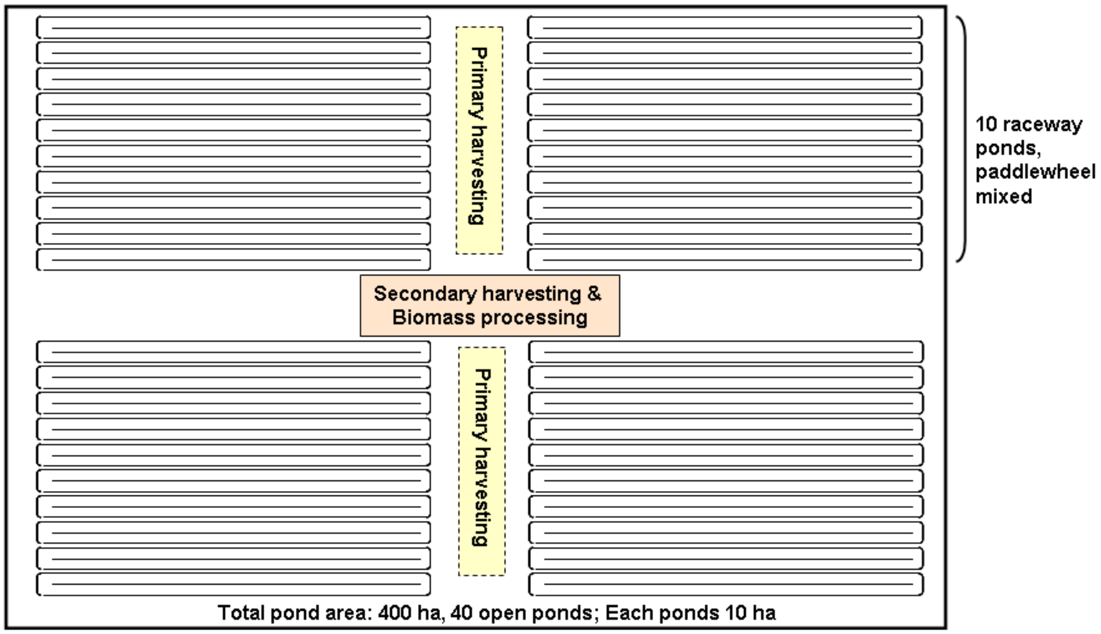


Figure S2: Layout of algae pond system (not to scale). The system has a total of 40 growth ponds, each with an area of 10 ha. Total growth pond area is 400 ha. Each raceway pond has two channels, with a length ~1 km each. Each channel has a width of ~48 m. Pond depth is 30 cm. Primary and secondary harvesting (dewatering) units are nominally positioned as shown. Total land area for the facility is estimated to be ~450 ha.

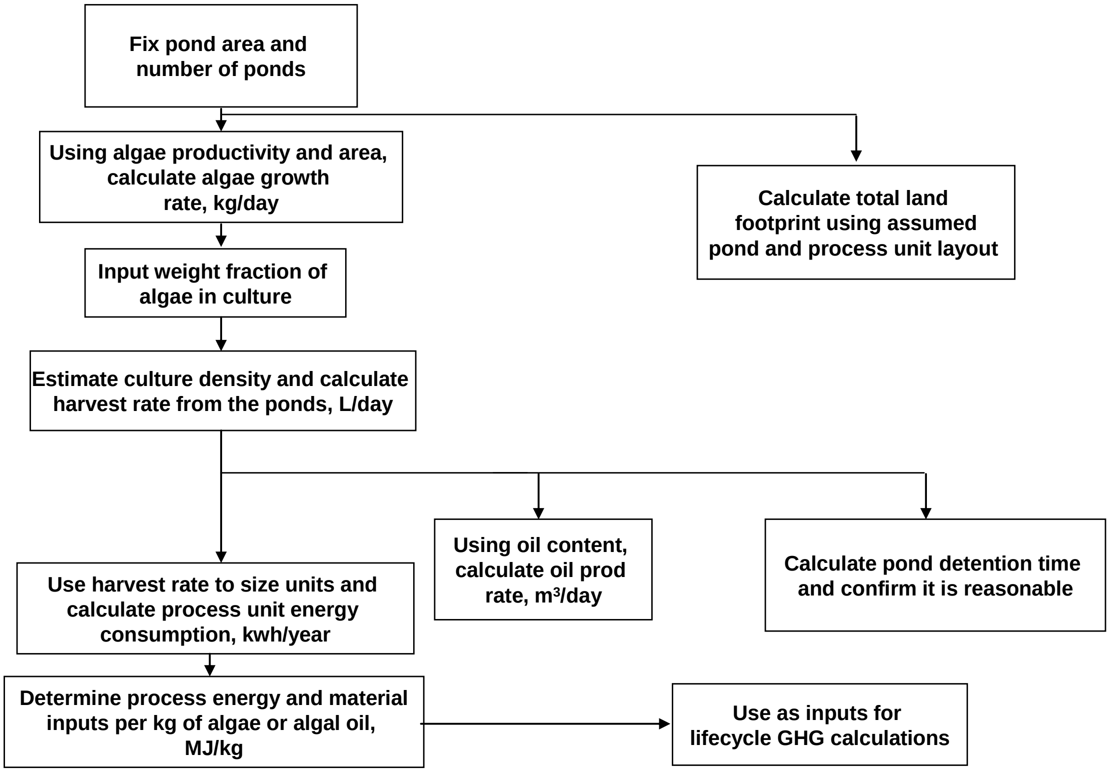


Figure S3: Overview of calculation methodology adopted for the GHG calculations. Pond area is fixed and algae biomass productivity and composition are inputs to the model. Energy and material inputs for process units estimated using vendor data and the authors' collective engineering judgment.

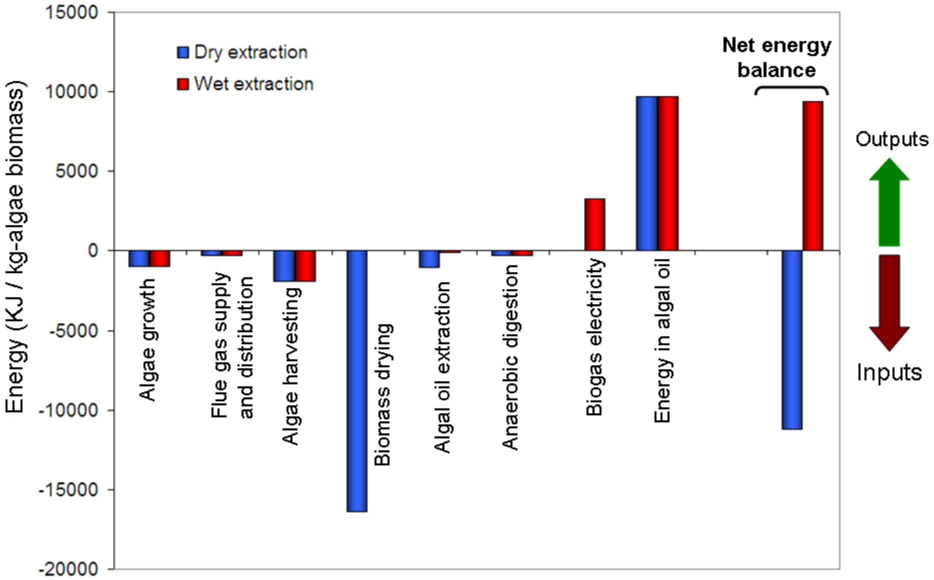


Figure S4: Energy inputs and outputs for the nominal dry and wet extraction technology sets. Positive numbers represent energy outflows, negative numbers represent energy inputs. Focus is on algal oil (TAG) production i.e. oil upgrading step is not shown. Different energy forms are treated equivalently in this figure. Estimate for steam consumption in the wet extraction step from ref. 43. Primary energy burden in dry extraction is from biomass drying. In these nominal technology sets, CO_2 supply is not a significant contributor because we have assumed flue gas feed to the ponds (MEA scrubber not required), co-location of the pond-system and the make-up CO_2 source, and large ducts to distribute the flue gas on-site.

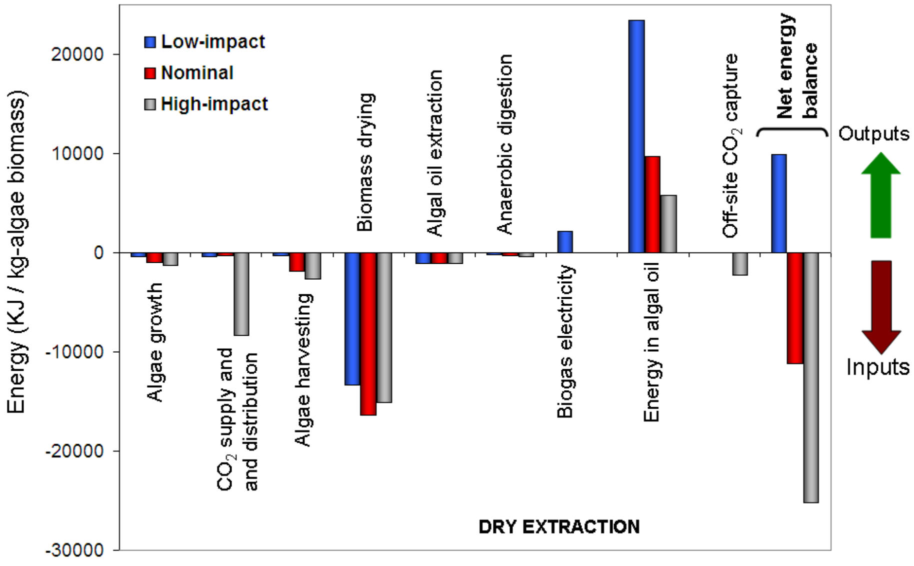


Figure S5: Energy inputs and outputs for the low-impact, nominal and high-impact dry extraction cases. Positive numbers represent energy outflows, negative numbers represent energy inputs. Focus is on algal oil (TAG) production i.e. oil upgrading step is not shown. Different energy forms are treated equivalently in this figure. For technology and parameter assumptions, see Table 1 of the main paper. In the high-impact case, pure CO_2 is fed to the growth ponds – energy debits associated with the MEA capture process on-site are included in the CO_2 supply and distribution category, while the debits associated with capturing make-up CO_2 are shown as a separate category (off-site CO_2 capture).

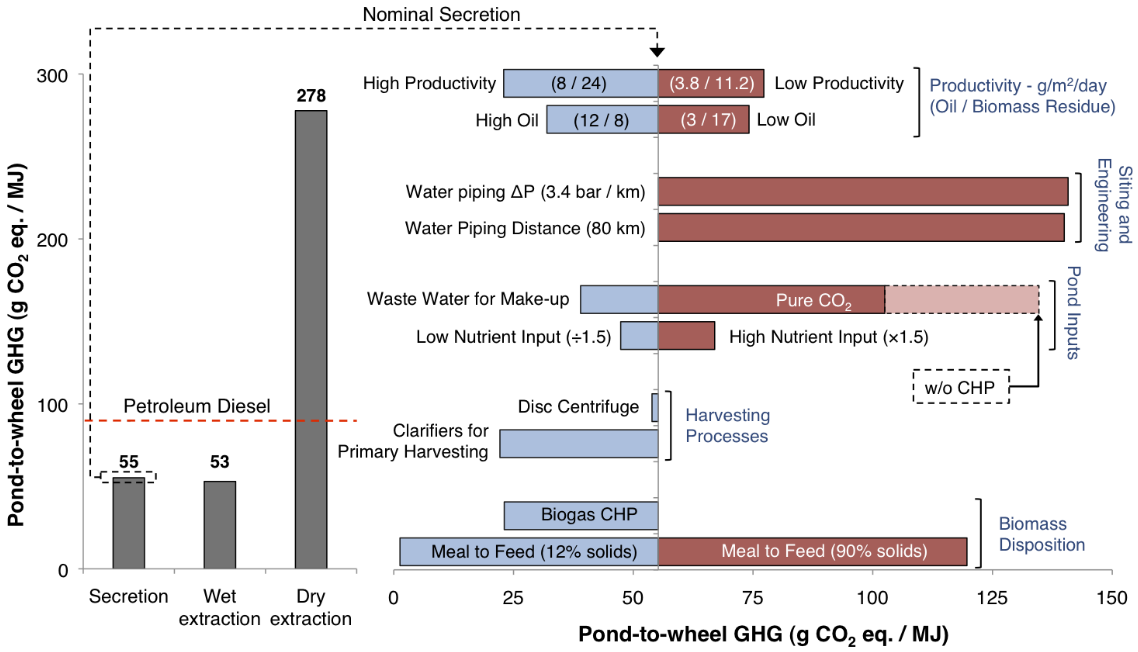
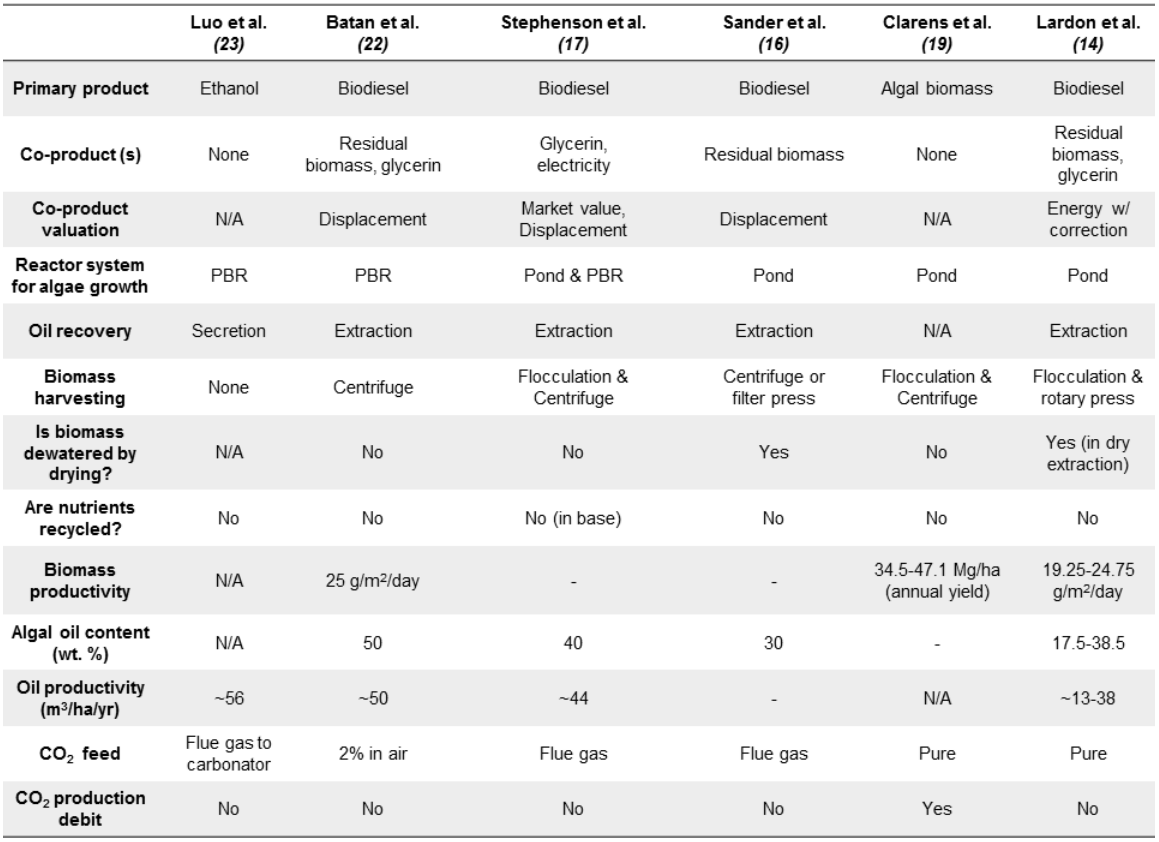


Figure S6: Pond-to-wheel GHG estimates for the nominal technology sets (left); parameter / scenario assessment for nominal secretion (right). Productivity and process technology assumptions for the nominal secretion technology set are in Table S10. A local sensitivity analysis was deemed appropriate because trends in GHG are largely independent of parameter coupling. Note that in the figure to the right, ‘meal’ refers to the residual biomass harvested from the ponds.

Supporting Tables



	Luo et al. *(23)*	**Batan et al.** *(22)*	**Stephenson et al.** *(17)*	**Sander et al.** *(16)*	**Clarens et al.** *(19)*	**Lardon et al.** *(14)*
Primary product	Ethanol	Biodiesel	Biodiesel	Biodiesel	Algal biomass	Biodiesel
Co-product (s)	None	Residual biomass, glycerin	Glycerin, electricity	Residual biomass	None	Residual biomass, glycerin
Co-product valuation	N/A	Displacement	Market value, Displacement	Displacement	N/A	Energy w/ correction
Reactor system for algae growth	PBR	PBR	Pond & PBR	Pond	Pond	Pond
Oil recovery	Secretion	Extraction	Extraction	Extraction	N/A	Extraction
Biomass harvesting	None	Centrifuge	Flocculation & Centrifuge	Centrifuge or filter press	Flocculation & Centrifuge	Flocculation & rotary press
Is biomass dewatered by drying?	N/A	No	No	Yes	No	Yes (in dry extraction)
Are nutrients recycled?	No	No	No (in base)	No	No	No
Biomass productivity	N/A	25 $g/m^2/day$	-	-	34.5-47.1 Mg/ha (annual yield)	19.25-24.75 $g/m^2/day$
Algal oil content (wt. %)	N/A	50	40	30	-	17.5-38.5
Oil productivity ($m^3/ha/yr$)	~56	~50	~44	-	N/A	~13-38
CO_2 feed	Flue gas to carbonator	2% in air	Flue gas	Flue gas	Pure	Pure
CO_2 production debit	No	No	No	No	Yes	No

Table S1: Recent studies on the environmental performance of algae. We estimated oil productivity values from biomass productivity and oil content in the studies where the parameter was not reported explicitly. Significant disparity in underlying assumptions is evident. This makes a consistent comparison of past work challenging.

Parameter description	**Weight, grams/kg-dry algae**	**LHV, MJ/kg**
Total lipids	350	39
Carbohydrates	200	17
Proteins	450	23

Table S2: Algae composition in the nominal dry and wet extraction technology sets. Weights shown are per kg of dry algal biomass. In the nominal cases, the extractable lipid fraction is assumed to be 250 grams / kg-dry algae. The extractable lipids are assumed to be in the form of triacylglycerides.

Parameter description	Nominal value	Units
Algae biomass productivity	20	g/m^2/day
Algae steady state concentration	300	ppm
Pond detention time (calculated)	4.7	days
Total oil content	35	%
Extractable oil content	25	%
Oil extraction efficiency	70	%
Overall pond mixing efficiency	42	%
Total CO_2 input (calculated)	2.1	kg/kg-algae
CO_2 feed type	Flue gas, 13 mole% CO_2	
Make-up CO_2 transport	8 (in essence, co-located)	km
Pond CO_2 capture efficiency	90	%
Culture medium salinity	40	ppt
Make-up water salinity	20	ppt
Pond evaporation rate	0.5	cm/day
Blowdown ratio	1	
Make-up water transport	8	km

Table S3: Algae growth and pond system assumptions in the nominal extraction technology sets.[3,4,40, 54, 60-64] We have assumed that the algae facility and the make-up CO_2 source are co-located. Culture medium is saline with brackish make-up to compensate for losses associated with evaporation and blowdown. Pond detention time has been chosen to match values that have been reported in the literature. Algae biomass productivity and extractable lipid fraction are based on values that are expected to become viable in the near-to-mid term. Process technology assumptions in Table 1 of the main paper. Additional details on water-related assumptions in Section 9.

Nutrient	Amount (grams/kg-biomass)	Source / comments
Nitrogen	100	Redfield ratios, sea water culture
Phosphorous	12	
Potassium	< 1	
Magnesium	< 1	
Iron	5	
Others	< 1	
Other assumptions		
Nutrient use efficiency	90%	assumed
Nutrient recycle efficiency	60%	based on ref. 4

Table S4: Nutrient inputs for algae growth. Inputs are estimated using Redfield ratios, assuming a sea water culture. A nutrient use efficiency of 90% is assumed. 60% of nutrients are recycled via the anaerobic digester effluent stream.

Parameter description	Nominal value	Units	Source / ref.
Belt drying system (for dry extraction technology set)			Vendor inputs, based on commercial sludge dryers
Heat input	3367	kJ / kg-water	
Biomass concentration at outlet	90	wt %	
'Wet' extraction			
Power input	0.02	kWh / kg-algae	Estimated based on refs. 6, 43 & process model calculations
Steam input (process model)	0.68	kg / kg-algae	
KOH	0.04	kg / kg-algae	
Furnace efficiency to generate steam from natural gas	85	%	
Two-stage anaerobic digester			
Biogas yield	~1	m^3/ kg	49
First stage digester efficiency	60	%	
Second stage digester efficiency	10	%	
Volatile solids (VS) loading	2.5	kg VS / m^3.day	
Mixing power per unit volume of digester	0.01	kW / m^3	
Parameters to calculate pumping load			
Pressure drop in pipelines for water	0.5	bar / km	66
Pumping efficiency	80	%	67

Table S5: Parameters for various process units in the nominal extraction technology sets. The steam input shown for 'wet' extraction was estimated by the authors using a simple process model; note that the steam input reported in ref. 43 has been used in the analyses described in the main paper. Inputs for the primary and secondary harvesting units are shown in Table S6. Inputs for dry solvent extraction are in Table S7, while inputs for oil upgrading are in Table S8.

Parameter description	Nominal value	Units
Dissolved air flotation		
Capacity	1249	m^3 / hr
Biomass concentration at outlet (float)	2.25	wt %
Biomass concentration in recycle (effluent)	15	mg / L
Flocculent input	5	ppm
Power for one DAF	132	kW
Decanter centrifuge		
Capacity	227	m^3 / hr
Biomass concentration at outlet (concentrate)	12	wt %
Biomass recovery efficiency	95	%
Power for one centrifuge	317	kW

Table S6: Operating variables and power requirements for harvesting (dewatering) units. Data based on vendor inputs. Data shown in the table are for one process unit. Based on the flow rates that need to be handled, more than one harvesting unit may be required and would operate in parallel. Power inputs to pump liquid streams from and to the harvesting units are considered separately.

Parameter description	Nominal value	Units
Total energy input	4612	kJ / kg-oil
Power input	8	%
Natural gas input	84	%
Hexane input	8	%

Table S7: Dry solvent extraction energy and material inputs. Data based on solvent extraction process used for soy oil recovery, but adapted for recovery of oil from algae biomass.[24, 41]

Parameter description	Nominal value	Units
Hydrogen input	2.72	kg / 100 kg feed
Power input	5.15	kWh / 100 kg feed
Natural gas input	195	kJ / kg-diesel
Fuel gas produced	5.02	kg / 100 kg feed
Yield of diesel	85.18	kg / 100 kg feed

Table S8: Algal oil (TAGs) hydroprocessing inputs. Data are based on soy oil hydroprocessing. We have assumed that the hydroprocessing of algal oil TAGs is equivalent to soy oil hydroprocessing.

Parameter description	Nominal value	Units
Residual biomass composition		
Lipid	133	g/kg
Carbohydrates	267	g/kg
Protein	600	g/kg
Residual biomass productivity	15	$g/m^2/day$
Secreted oil productivity	5	$g/m^2/day$
Steady state biomass concentration in the ponds	225	ppm
Pond detention time (calculated)	4.6	days
Oil/(oil+water) volume ratio	0.09	

Table S9: Selected inputs and assumptions in the nominal secretion technology set. Productivity parameters chosen to be roughly equivalent to the nominal extraction technology set.

	Low-Impact	Nominal	High-Impact
Scenario Options			
Make-up (from power plant) and recycle CO_2	Flue gas (with limited heat integration)	Flue gas	Pure
Make-up water	Municipal waste water with nutrient value	Brackish	Brackish
Nitrogen nutrient type	Ammonia	U.S. Average	Ammonium nitrate
Primary harvesting	Clarifiers	Dissolved air flotation	Dissolved air flotation
Secondary harvesting	Disc centrifuge	Decanter centrifuge	Decanter centrifuge
Digester sludge disposition	Soil conditioner with fertilizer value	Waste	Waste
Parameter Options			
Secreted oil productivity ($g/m^2/day$)	19.2	5	2.25
Residual biomass productivity ($g/m^2/day$)	2.5	15	12.75
Steady state residual biomass concentration in ponds (ppm)	200	225	200
Pond mixing efficiency (%)	60	42	42
Nutrient inputs (g/kg-residual biomass)	÷ 1.5	N: 154, P: 18, Fe: 8	× 1.5

Table S10: Key assumptions in low-impact, nominal, and high-impact cases for secretion. The following are true for all cases: algae are grown in saline, paddlewheel mixed open raceway ponds; residual biomass is digested to form biogas for conversion to power; nutrient recycle efficiency fixed at 60% and nutrient utilization efficiency of 90% was assumed. Brackish make-up water transport was 8 km with pipeline pressure drop for liquids of 0.5 bar/km. Pond operation is the same in the nominal and high-impact cases, (i.e., fixed detention time for biomass in the ponds, ~4.6 days). In the low-impact case, a longer detention time was assumed, ~22.3 days, for the residual biomass harvested from the pond-system. Data inputs and operating parameters for the harvesting units chosen for the low-impact case are shown in Table S11**.**

Parameter description	Nominal value	Units
Clarifier		
Overflow rate	18	$m^3/m^2.day$
Depth of clarifier	4	m
Clarifier volume	3900	m^3
Biomass concentration in clarifier concentrate	2.25	wt %
Biomass concentration in clarifier effluent	15	mg / L
Clarifier rake drive	0.4	kW
Disc centrifuge		
Capacity	91	m^3/hr
Biomass concentration at outlet (concentrate)	18	wt%
Biomass recovery efficiency	95	%
Power for one centrifuge	52	kW

Table S11: Harvesting (dewatering) units used in the low-impact secretion and extraction cases: operating and design variables and power requirements. Note that the data shown in the table are for one harvesting unit. Based on the flow rates that need to be handled, more than one harvesting unit may be required and would operate in parallel. Data are based on vendor inputs, the collective engineering judgment of the authors and refs. 3 & 49 for the clarifier. Power inputs to pump liquid streams from and to the harvesting units are considered separately. As described in the main paper, the effluent biomass concentration from the centrifuge can have a significant indirect impact on the drying energy requirement and therefore, GHG, in the dry extraction case. A disc centrifuge was used in the low-impact cases as data was readily available – using a decanter centrifuge with a higher effluent solids wt% would have a similar impact on GHG.

Parameter description	Nominal value	Units
Brackish make-up to ponds		
Evaporation rate	0.5	cm/day
Make-up water TDS	20	ppt
Blowdown ratio	1	
Steady state pond TDS	40	ppt
Fresh make-up to ponds		
Evaporation rate	0.5	cm/day
Make-up water TDS	1	ppt
Blowdown ratio	0.05	
Steady state pond TDS	20	ppt
Process unit freshwater inputs		
Dry solvent extraction	3.3	kg/ton-algae
Drying system cooling loop	0.7	kg/kg-algae
On-site electricity generation	0.8	L/kWh
Hydroprocessing	1	kg/kg-diesel
MEA capture	1.2	L/kg-CO_2

Table S12: Primary inputs and assumptions in the freshwater consumption calculations for algal biofuels. The evaporation rate is based on pan evaporation data. Steady state TDS levels in the ponds are assumed. Blowdown ratios have been estimated to maintain the desired pond salinity. Process unit freshwater consumption factors based on vendor inputs and literature data.[11,40, 48,70,71]

Fuel product	Freshwater consumption (L-water/L-fuel product)			
	Feedstock production	Conversion to fuel product	Total	Ref.
Petroleum gasoline	1.4-4.6	1.5	2.8-5.8	12
Corn ethanol	7-1400	3.6	10.6-1403.6	12,73
Soy biodiesel	Up to 9000	1-3	2-9002	11,13

Table S13: Freshwater consumption for petroleum-derived gasoline and first generation biofuels. The feedstock production ranges for corn ethanol consider all regions of the U.S. For petroleum, freshwater consumption shown is for conventional resources.