SAND2015-0379B

Chapter 17. Resource Requirements for Algal Biofuels

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[2] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Abstract

Producing algal biofuels requires material assets and inputs that include land, water, nutrients, suitable growing conditions (sunlight, climate), energy, biomass cultivation and processing facilities infrastructure, and capital for industry development and operations (financial and human). Various aspects of this have been touched on in earlier chapters. However, this chapter focuses specifically on the issues associated with natural resource demand and potential constraints for sustainable biofuels production scale-up based on autotrophic microalgae. The resource requirement challenges involve the sourcing and competing uses of land, water and key nutrients (C, N and P) at the large aggregated quantities needed to significantly contribute to the demand for energy and fuel supplies at national scales. The resulting resource requirements can be expected to impose constraints on the level of algal biomass and biofuels production scale-up that can be supported. This chapter provides a high-level overview of the status and prospects for the natural resource demand and constraint challenges for algal biofuels. Some discussion is within the context of the USA, however the issues generally apply globally.

Key Terms

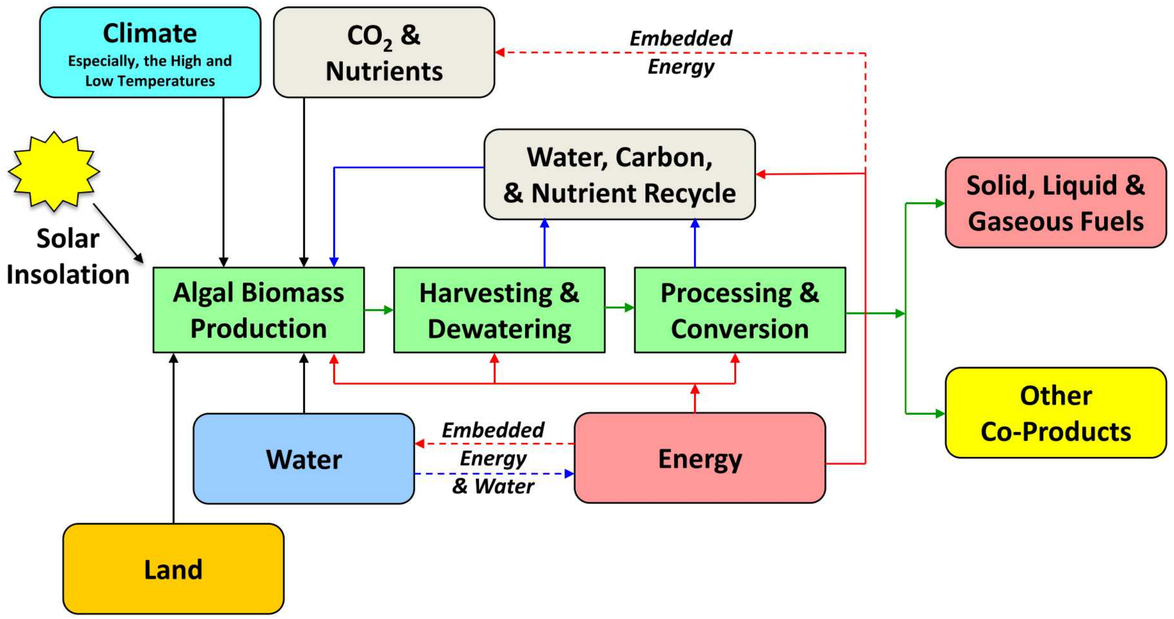
Algal Biofuel: *Energy storage products in solid, liquid, or gaseous form derived from the processing and conversion of algal biomass or extracted neutral lipids. Algal biofuel for transportation most frequently refers to liquid fuels that can include alcohols, biodiesel, and infrastructure-compatible hydro-treated renewable hydrocarbon fuels (gasoline, diesel, aviation) that are drop-in equivalent to petroleum based fuels.*

Resources: *Material assets and inputs required for production of algal biomass and biofuels that include land, water, nutrients, suitable growing conditions (sunlight, climate), energy, cultivation and processing facilities and infrastructure, and operating capital (financial & human). Chapter focus is on key natural resource demands and potential constraints for sustainable algae production scale-up that primarily involve the sourcing and sustainable use of land, water, and key nutrients (C, N, P).*

Nutrients: *Chemical elements and compounds (inorganic and organic) required for healthy, robust, and productive algal biomass growth. Key elemental nutrients required for autotrophic algae production are inorganic carbon (from CO_2), nitrogen, and phosphorus. Heterotrophic algae production requires organic carbon in the form of sugars or other simple organic molecules.*

Introduction

The production of biomass from autotrophic microalgae, and the subsequent processing and conversion of that biomass into fuels and other useful co-products, requires the utilization of various resources, as illustrated in Figure 1. To make a significant impact on fuel markets, algal biofuel production must be capable of scaling up to many billions of liters per year (BLY). Producing algal biomass feedstock and fuels in such high volumes will impose significant demands on land, water, the major nutrients nitrogen (N) and phosphorus (P), and inorganic carbon (C) in the form of CO_2 needed to grow photosynthetic microalgae. Recent investigations suggest that challenges and limitations to affordable and sustainable resource supply can be expected to emerge as the projected level of algal biofuel production increases [1-8].

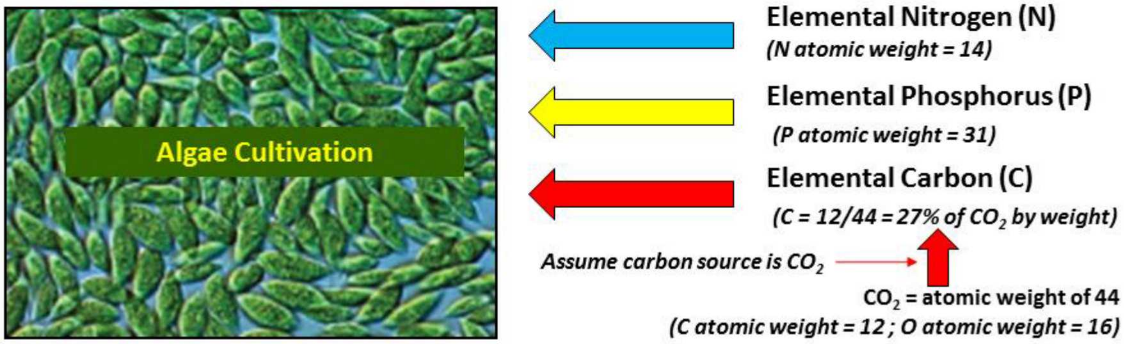


Resources and Environmental Factors and Parameters

Climate	**Water**	**Nutrients**	**Land**	**Energy**
Solar Insolation	Surface/Ground	CO_2, Organic Carbon	Location/Use Category	Electric Power
Temperature	Location/Access	N, P, Other	Topography	Process Heat
Evaporation	Supply/Allocation	Sources/Supplies	Soil type/Ground Cover	Fuel Resource Use
Precipitation	Salinity/Chemistry	Cost & Availability	Geology/Hydrology	Life Cycle Emissions
Weather Events	Sustainability	Sustainability	Ownership/Access	Cost & Availability
			Structures & Facilities	

Figure 1. Simplified illustration of the algal biofuels supply chain showing key resource inputs spanning the operations of biomass production through downstream processing and conversion to fuels and possible co-products. Adapted from [7].

These are important considerations for managing expectations and providing insight for making informed decisions, for both policy and investments in technical research and business development. Production of fuels from photosynthetic algae is not yet a commercially viable industry, and is therefore currently done at relatively small research, pilot, and demonstration scales that generally do not involve integrated end-to-end operations. For this reason, objective and verifiable data on the long-term operational performance and associated resource utilization by large scale integrated systems and processes for algal biomass production and processing does not yet exist. However, approximate high-level estimates for resource demand can be made based on assumed levels of algal biomass productivity (ash free dry weight basis: AFDW) and the application of basic stoichiometric mass balance (shown in Figure-2) and simple scaling relationships (shown in Table-1), that have been derived from straightforward analyses reported elsewhere [1,2,7]. These analyses generally ignore the details of technical systems approaches, processes, and integrated configurations, which remain immature and are still emerging for large scale algal biofuel production. The exception is the assumed use of open algal biomass cultivation systems subject to evaporative water loss, while ignoring any periodic cultivation system water "blow-down" that might be needed.



<u>Idealized mass-balance assumptions and steps for estimating N, P, and C requirements</u>

1) Assume inputs of elemental N, P, and C (from CO_2 sources) are transferred to, and taken up by, algae biomass with no losses and 100% efficiency
2) Assume average C:N:P atomic ratio = 106:16:1 (Redfield Ratio) in ash-free dry weight (AFDW) algae biomass with ~ 50% carbon content (by weight)
3) C:N:P mass ratio in AFDW algae then becomes: (106x12):(16x14):(1x31) = 1272:224:31
4) With 50% C content by weight, the C:N:P mass ratio of 1272:224:31 converts to a mass percentage ratio of 50:(224x50/1272):(31x50/1272) = 50% C : 8.8% N : 1.22% P

Resulting requirements for each metric ton (1000 kg) of AFDW algal biomass produced:

~ 88 kg elemental N
~ 12 kg elemental P
~ 500 kg elemental C
~ 1830 kg of CO_2 ... *Rule-of-thumb: Mass CO_2 / Mass algae (AFDW) ~ 2*

Figure 2. Idealized mass balance estimates for inorganic carbon (C), nitrogen (N), and phosphorus (P) requirements for algal biomass production that are used in the scale-up calculation results summarized in Table-2. Adapted from [2, 7].

Although energy is a key resource requirement, energy is also largely excluded from this discussion simply because the demand for energy in its various forms will be highly dependent on system details and the specific geographical location and physical distribution of cultivation and processing facilities. While limited in precision and subject to uncertainties, this level of analysis provides reasonable bounding estimates for resource demands that can be expected for algal biofuels production scale-up. Additional financial, institutional, and human capital resources, not shown in Figure 1, will also be required to develop, operate, and maintain systems, facilities, and product distribution. These resource topics are beyond the scope of this discussion.

Approach and Key Assumptions

Table-2 provides a summary of high-level resource requirement estimates for algal biofuel scale-up, based on the idealized mass balance requirement assumptions for elemental N, elemental P, elemental C and CO_2 shown in Figure-2, and the key parameter definitions and scaling relationships shown in Equations 1-5 of Table-1. The idealized elemental mass balance ratio for the AFDW algal biomass illustrated in Figure-2 is assumed to be the Redfield ratio (C:N:P = 106:16:1), with a carbon content of about 50%.

The downstream pathway assumed for fuel production is the extraction of neutral lipids (e.g., oils such as triacylglycerides - TAGs) from harvested and dewatered algal biomass. This represents the dominant approach being pursued for algal biofuels, whereby the extracted oil provides high-quality feedstock that can then be converted to various hydrocarbon fuels ranging from blend stock, such as biodiesel produced by transesterification processing, to infrastructure-compatible renewable diesel, gasoline, or aviation fuel produced using more elaborate refining techniques. It should be noted that other downstream processing paths, such as the combination of biomass lipid extraction with the biochemical conversion of the carbohydrate fraction to alcohols, or the hydrothermal liquefaction (HTL) of whole algal biomass into a biocrude fraction that can be upgraded to fuels using refining techniques, could also be dealt with in a similar way through the adjustment of parameters and scaling relationships. Example studies of such pathway options suggest that yields on the order of 493 liters (130 U.S. gallons) of gasoline equivalent fuel (GGE - on an energy content basis) per U.S. ton of ash free dry weight (AFDW) algal biomass may eventually be feasible [9, 10], which is equivalent to about 542 liters (143 U.S. gal) of gasoline equivalent fuel per metric ton. However, these are emerging pathways that have yet to be adequately demonstrated with publically available performance data at larger scales, and will not be dealt with further here.

Key parameters used to characterize algal biomass and oil productivity in open pond type cultivation systems are P_{BD} [g{algae} m^{-2} d^{-1}], which represents the annual average daily biomass (AFDW) productivity in grams per square meter per day, and L [%], which represents the percent content (by weight) of neutral lipids in the AFDW biomass. Using the relationships given in Eq 1 and Eq 2 of Table-1, these parameters can be equated to annual average biomass (AFDW) productivity P_{BM} [mt {algae} ha^{-1} yr^{-1}], in metric tons per hectare per year, and annual average neutral lipid productivity P_L [l {lipid} ha^{-1} yr^{-1}], in liters (oil) per hectare per year. Assumed here for simplicity is that the oil content can be extracted with 100% efficiency and that the resulting quantity of algal oil produced will be the proxy for the amount of algal biofuel produced. This neglects the process-dependent conversion efficiency factors that would need to be applied in going from algal oil to specific end-use fuels. Assumed levels of biomass productivity considered here, and shown in Table-2, are P_L = 9361 [l ha^{-1} yr^{-1}] (~1000 U.S. gallons per acre per year); 28084 [l ha^{-1} yr^{-1}] (~3000 gal ac^{-1} yr^{-1}], and 60848 [l ha^{-1} yr^{-1}] (~6500 gal ac^{-1} yr^{-1}]. Assumed levels of oil content are L = 10%, 20%, 35%, and 50%. These values represent potentially achievable low, medium, and high algal oil productivities and % oil content in the biomass (AFDW) for autotrophic algae based on the literature [11-15].

The degree of algal biofuel scale-up is determined by targeting the total desired level of annual neutral lipid (oil) production T [BLY], in billions of liters per year. Assumed here is a range for T of 19 BLY (~5 billion U.S. gallons per year – BGY); 37.9 BLY (~10 BGY); 75.8 BLY (~20 BGY); and 190 BLY (~ 50 BGY), as shown in Table-2. These represent levels of aggregated scale-up that would be significant for transportation fuel markets. As a reference point, 50 BGY is the approximate level of total annual diesel fuel use in the U.S. for transportation. Using Eq 3 in Table-1 gives the estimated land area A [ha], in hectares, required for the active algae cultivation area based on the assumed values for T [BLY] and P_L [l {lipid} ha^{-1} yr^{-1}], as shown in Table-2. For simplicity, this area neglects the additional land required, typically estimated to be perhaps another 15-20%, needed for other system and configuration dependent facilities and downstream processing infrastructure. From Eq 4 in Table-1 the total algal biomass (AFDW) produced annually, B_M [mt {algae} yr^{-1}], in metric tons per year, can be estimated from assumed levels of T [BLY] and L [%]. Water requirements are assumed to be dominated by replacement of evaporative loss from open cultivation systems, which is estimated here by applying Eq 5 in Table-1 using an assumed annual average evaporation rate E_{WL} [m yr^{-1}], in meters per year, applied over the total active algae cultivation area A [ha], in hectares, to give total annual make-up water demand W_M [BLY], in billions of liters per year. The assumed values for evaporative water loss rate, E_{WL}, considered here for illustration and shown in Table-2, are 1 [m yr^{-1}], 1.5 [m yr^{-1}], and 2.0 [m yr^{-1}]. These values represent a range of annual average evaporative water loss typical of many regions of interest for algae production, although higher losses approaching or exceeding 3 m yr^{-1} can occur. Actual evaporative water loss at any given location will be very site-specific and dependent in a complex way on local meteorological conditions and cultivation water salinity. The estimated requirements for CO_2, elemental N, and elemental P, all in metric

Table-1. Approximate functional relationships and parameter definitions for resources.

Functional Relationships – Equations (Eq)	Parameter Definitions	Eq #
Annual Average Algal Biomass and Oil Productivity and Requirements for Land and Make-up Water		
P_{BM} [mt {algae} ha^{-1} yr^{-1}] ~ 3.651 x P_{BD} [g{algae} m^{-2} d^{-1}] ~ 0.092 x P_L [l {lipid} ha^{-1} yr^{-1}] / L [%]	P_{BM} = annual average algae productivity P_{BD} = daily average algae productivity	1
P_L [l {lipid} ha^{-1} yr^{-1}] ~ 39.67 x L [%] x P_{BD} [g (AFDW) m^{-2} d^{-1}]	P_L = annual average lipid (oil) productivity L = algal biomass lipid content in % (mass)	2
A [ha] ~ 10^9 x T[BLY] / P_L [l ha^{-1} yr^{-1}]	A = algae cultivation surface area required T = total annual lipid (oil) production	3
B_M [mt {algae} yr^{-1}] ~ 1.3215 x 10^9 x T [BLY] / L [%]	B_M = annual ave. algal biomass production	4
W_M [BLY] ~ 10^{-2} x E_{WL} [m yr^{-1}] x A [ha] ~ 10^7 x E_{WL} [m yr^{-1}] x T [BLY] / P_L [l ha^{-1} yr^{-1}]	W_M = annual make-up water required E_{WL} = annual evaporative water loss rate	5
Relationships for Analysis of Daylight Hour Utilization by Algae of CO_2 Emissions from Power Plants		
C_D [kg{CO2}/d] = C_P [kg{CO_2}/d] *(assuming 100% efficiency for CO_2 capture & delivery to algae cultivation system)* = G [MW] x R_G [kg{CO_2}/MWh] x T_G [h/d]	C_D = daily delivery of CO_2 to algae cultivation system C_P = daily source production of CO_2 G = power plant generation capacity R_G = power plant emissions rate T_G = daily power plant operation time	6
C_A [kg{CO_2}/d] = η_E x C_D [kg{CO_2}/d] x T_{SH} [h/d] / T_G [h/d] = C_{UF} [g{CO_2}/g{algae}] x M_A [kg{algae}/d] ~ 2 x M_A [kg{algae}/d]	C_A = daily algal CO_2 consumption C_{UF} = carbon utilization factor = mass of CO_2 / mass of algae ~ 2 η_E = CO_2 utilization efficiency ~ 0.7	7
M_A [kg{algae}/d] = P_{BD} [g/(m^2-d)] x S_A [m^2] x 10^{-3} [kg/g] = 2.740 x M_{AA} [mt{algae}/yr]	M_A = daily algal biomass production S_A = algae cultivation area required to consume daylight pwr plant CO_2 emissions under assumed conditions	8
S_A [ha] = S_A [m^2] x 10^{-4} = 0.1 x (η_E/C_{UF}) x G [MW] x R_G [kg{CO_2}/MWh] x T_{SH} [h/d] / P_{BD} [g{algae}/(m^2 d)]	T_{SH} = average daily hours of sunlight (assumed to be ~ 8 hours/day) ≤ T_G, where T_{SH} is assumed to overlap entirely within TG	9
C_{PA} [mt{CO_2}/yr] = 0.365 x G [MW] x R_G [kg{CO_2}/MWh] x T_G [h/d]	C_{PA} = annual power plant CO_2 emissions T_G = daily generator operating hours	10
C_{AA} [mt{CO_2}/yr] = 0.256 x G[MW] x R_G [kg{CO_2}/MWh] x T_{SH} [h/d]	C_{AA} = annual CO_2 consumed by algae	11
M_{AA} [mt{algae}/yr] = C_{AA} [mt{CO_2}/yr] / C_{UF} ~ 0.5 x C_{AA}	M_{AA} = annual algal biomass production	12
G_{CO} [%] = 100 x C_{AA} / C_{PA} = 100 x η_E x T_{SH}/T_G ~ 70 x T_{SH}/T_G	G_{CO} = gross carbon offset factor	13
Units of measure, abbreviation nomenclature, and assumed R_G emissions values (alphabetical order)		
AFDW = ash free dry weight; BLY = billions of liters per year; d = day; g = gram; g{algae} = grams of algae (AFDW); h= hour; ha = hectare = 10^4 m^2; kg = kilogram; kg{algae} = kilograms algae (AFDW); kg{CO_2} = kilograms of CO_2; l = liter; l {lipids} = liter of algal lipid (oil); m = meter; mt = metric ton; mt{algae} = metric tons algae (AFDW); mt{CO_2} = metric tons of CO_2; MW = megawatt; R_G(Coal) = Coal power plant emissions rate ~ 960 kg{CO_2}/MWh; R_G (NG) = natural gas power plant emissions rate ~ 600 kg{CO_2}/MWh; yr = year = 365 d		

Table-2. Estimates for land, make-up water, CO_2, and nutrients (N, P) for algae production.

Key Algae Biofuel Resource Requirements			Total Algal Oil Yield (T) Billion L Yr^{-1} [BLY]	Algal Oil (Lipid) Productivity (P_L): L Ha^{-1} Yr^{-1}											
				9,361				19,659				60,848			
				Oil Content %				Oil Content %				Oil Content %			
				10	20	35	50	10	20	35	50	10	20	35	50
Algal Biomass (AFDW) Productivity (P_{BM}): Metric Tons Ha^{-1} Yr^{-1}				86.1	43.1	24.6	17.2	181	90.5	51.7	36.2	560	279	160	112
Cultivation Land Area (A): Hectares x 10^6			19	2.02				0.964				0.311			
			37.9	4.05				1.93				0.623			
			75.8	8.1				3.86				1.25			
			190	20.2				9.64				3.11			
Evap. Water Loss (W_M): Billion Liters Yr^{-1} [BLY]	Annual Av. Evap. Rate for Open Ponds (E_{WL}) m Yr^{-1}	1	19	20246				9637				3114			
			37.9	40491				19274				6236			
			75.8	80983				38548				12431			
			190	202457				96370				31138			
		1.5	19	30317				14431				4663			
			37.9	60634				28862				9338			
			75.8	121269				57724				18615			
			190	303172				144310				46628			
		2	19	40440				19249				6220			
			37.9	80880				38499				12456			
			75.8	161760				76998				24830			
			190	404400				192494				62197			
Biomass Produced (AFDW) (B_M): Metric Tons Yr^{-1} x 10^6			19	174	87.2	49.8	34.9	174	87.2	49.8	34.9	174	87.2	49.8	34.9
			37.9	349	174	99.6	69.7	349	174	99.6	69.7	349	174	99.6	69.7
			75.8	697	349	199	140	697	349	199	140	697	349	199	140
			190	1743	872	498	349	1743	872	498	349	1743	872	498	349
CO_2 Requirements (stoichometric for ~50% carbon content AFDW)[a] Metric Tons Yr^{-1} x 10^6			19	347	174	99.6	69.7	347	174	99.6	69.7	347	174	99.6	69.7
			37.9	697	349	199	140	697	349	199	140	697	349	199	140
			75.8	1395	697	399	279	1395	697	399	279	1395	697	399	279
			190	3487	1743	996	697	3487	1743	996	697	3487	1743	996	697
N Requirements (stoichometric C_{106}:N_{16}:P_1 AFDW w/ ~50% C)[b] Metric Tons Yr^{-1} x 10^6			19	15.4	7.67	4.38	3.07	15.4	7.67	4.38	3.07	15.4	7.67	4.38	3.07
			37.9	30.7	15.3	8.77	6.14	30.7	15.3	8.77	6.14	30.7	15.3	8.77	6.14
			75.8	61.4	30.7	17.5	12.3	61.4	30.7	17.5	12.3	61.4	30.7	17.5	12.3
			190	153	76.7	43.8	30.7	153	76.7	43.8	30.7	153	76.7	43.8	30.7
P Requirements (stoichometric C_{106}:N_{16}:P_1 AFDW w/ ~50% C)[c] Metric Tons Yr^{-1} x 10^6			19	2.09	1.05	0.6	0.42	2.09	1.05	0.6	0.42	2.09	1.05	0.6	0.42
			37.9	4.18	2.09	1.2	0.84	4.18	2.09	1.2	0.84	4.18	2.09	1.2	0.84
			75.8	8.37	4.18	2.39	1.67	8.37	4.18	2.39	1.67	8.37	4.18	2.39	1.67
			190	20.9	10.5	5.98	4.18	20.9	10.5	5.98	4.18	20.9	10.5	5.98	4.18

[a] ~ 2 mass units of CO_2 per mass unit of algal biomass (AFDW) [b] ~ 88 kg elemental N per metric ton AFDW biomass

[c] ~12 kg elemental P for each metric ton AFDW algal biomass

tons per year, are shown in Table-2 for the various levels of assumed T [BLY], P_L [l ha^{-1} yr^{-1}], and L [%] considered here. This is based on applying the mass balance scaling relationships shown in Figure-2 to the estimated total annual average biomass produced B_M in metric tons per year.

Summary for Land:

The land requirements estimated in Table-2 to produce the minimum algal oil scale-up production target of 19 BLY (5 BGY) range from a low of 0.311 million ha (0.769 million ac) at a productivity of 60848 [l ha^{-1} yr^{-1}] (6500 gal ac^{-1} yr^{-1}) to a high of 2.02 million ha (5.00 million ac) at a productivity of 9361 l ha^{-1} yr^{-1} (1000 gal ac^{-1} yr^{-1}). For the maximum oil production scale-up target of 190 BLY (50 BGY), the land required is an order of magnitude higher and ranges from a low of 3.11 million ha (7.69 million ac) at a productivity of 60848 l ha^{-1} yr^{-1} (6500 gal ac^{-1} yr^{-1}) to a high of 20.2 million ha (50.0 million ac) at a productivity of 9361 l ha^{-1} yr^{-1} (1000 US gal ac^{-1} yr^{-1}). As a reference point, 16 million ha (39 million ac) represents about 10% of the total grassland and non-forested pasture in the lower-latitude half of the contiguous U.S. [2,7].

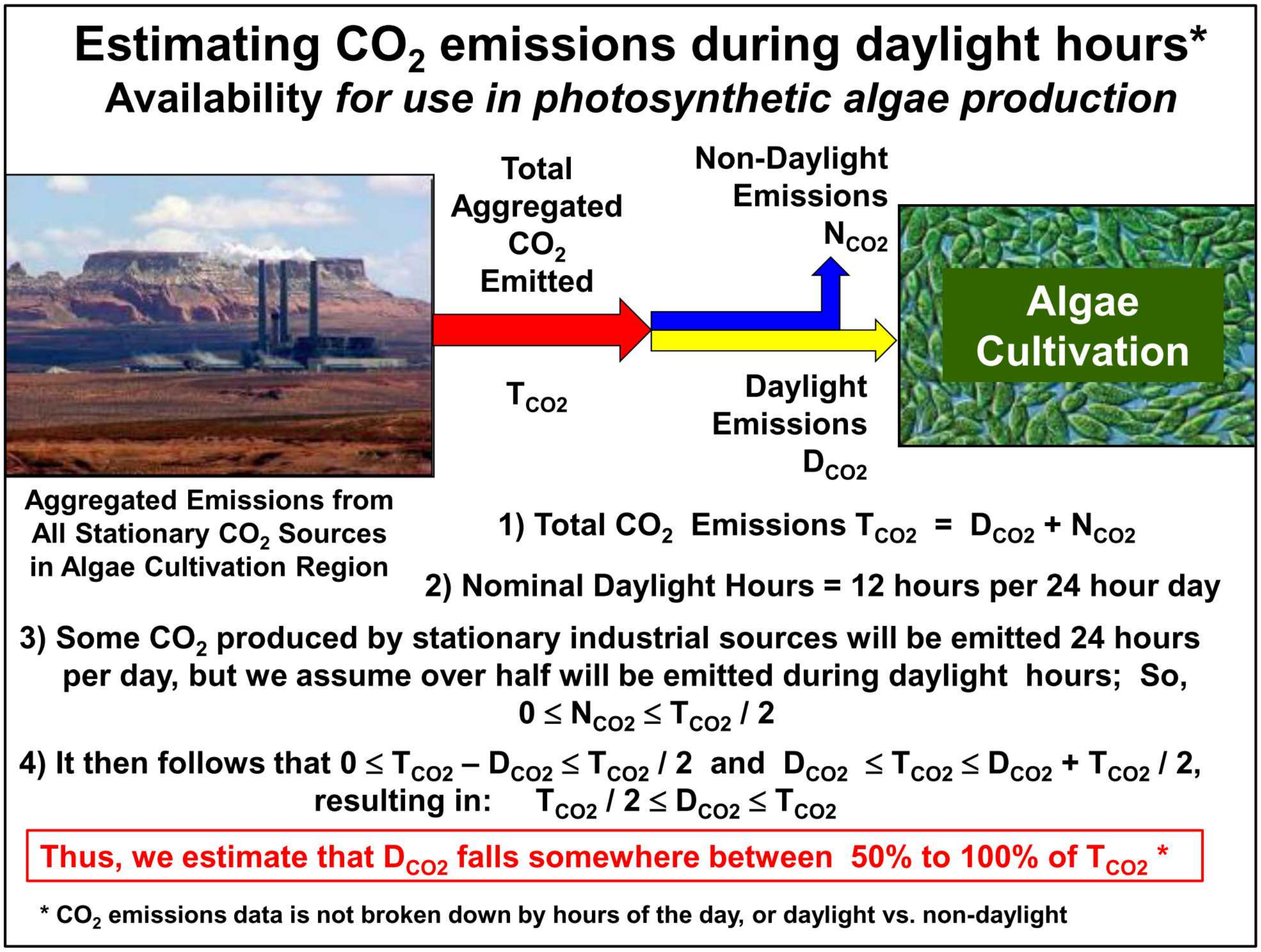
Summary for water:

Water requirements estimated in Table-2 to produce the minimum algal oil scale-up production target of 19 BLY (5 BGY), in a region with an evaporative loss rate of 1.00 m yr^{-1} (39.4 inches yr^{-1}), range from a low of 3114 BLY (822 BGY) at an oil productivity of 60848 l ha^{-1} yr^{-1} (6500 gal ac^{-1} yr^{-1}) to a high of 20246 BLY (5342 BGY) at a productivity of 9361 l ha^{-1} yr^{-1} (1000 gal ac^{-1} yr^{-1}). This represents water use intensity ranging from 164 to 1068 liter (or gal) of water per liter (or gal) of oil produced, with water use intensity improving as the oil productivity per unit area increases. For the maximum oil production scale-up target of 190 BLY (50 BGY), in a region with an evaporative loss rate of 2.00 m yr^{-1} (78.7 in yr^{-1}), the water required ranges from a low of 6220 BLY (1641 BGY) at an oil productivity of 60848 l ha^{-1} yr^{-1} (6500 gal ac^{-1} yr^{-1}) to a high of 404400 BLY (106702 BGY) at a productivity of 9361 l ha^{-1} yr^{-1} (1000 gal ac^{-1} yr^{-1}). This represents water use intensity ranging from 328 to 2134 liter of water per liter of oil produced, depending on oil productivity per unit cultivation area. As a reference point, 29700 BLY (~7800 BGY) represents about 25% of the total freshwater used for agricultural irrigation in the lower-latitude half of the contiguous U.S. [2,7].

Various suitability and climate factors will come into play with regard to the preferred location, availability, and use of land and water resources for algae production. Detailed discussion of these is beyond the scope of this chapter and can be found elsewhere [2-7, 12, 16].

Summary for CO_2:

The CO_2 requirement estimates given in Table-2 to produce the minimum algal oil scale-up production target of 19 BLY (5 BGY) ranges from a low of 69.7 million metric tons at 50% oil content to a high of 347 million metric tons at 10% oil content, regardless of the assumed level of algal oil productivity P_L. The CO_2 required to produce the maximum algal oil scale-up production target of 190 BLY (50 BGY) is an order of magnitude higher, ranging from a low of 697 million metric tons at 50% oil content to a high of 3487 million metric tons at 10% oil content. As a reference point, 370 million metric tons represents roughly 25%-to-50% of the total daylight hour emissions of CO_2 from stationary industrial sources compiled for the lower-latitude half of the contiguous U.S. [7]. The ambiguity that exits in estimating the daylight hour portion of CO_2 emissions that can be utilized for algae growth is illustrated in Figure-3, and is due to emissions statistics being reported as annual totals that do not break down emitted quantities by time of day.



Estimating CO_2 emissions during daylight hours*

Availability *for use in photosynthetic algae production*

1) Total CO_2 Emissions $T_{CO2} = D_{CO2} + N_{CO2}$

2) Nominal Daylight Hours = 12 hours per 24 hour day

3) Some CO_2 produced by stationary industrial sources will be emitted 24 hours per day, but we assume over half will be emitted during daylight hours; So,

$$0 \leq N_{CO2} \leq T_{CO2} / 2$$

4) It then follows that $0 \leq T_{CO2} - D_{CO2} \leq T_{CO2} / 2$ and $D_{CO2} \leq T_{CO2} \leq D_{CO2} + T_{CO2} / 2$, resulting in: $T_{CO2} / 2 \leq D_{CO2} \leq T_{CO2}$

Thus, we estimate that D_{CO2} falls somewhere between 50% to 100% of T_{CO2} *

*** CO_2 emissions data is not broken down by hours of the day, or daylight vs. non-daylight**

Figure-3. Ambiguity in estimating fraction of industrial CO_2 emissions during daylight hours.

The resulting CO_2 use intensity range represented in Table-2 is: 3.68 kg/liter (13.95 kg/gal) for 50% biomass oil content, 5.26 kg/liter (19.92 kg/gal) for 35% oil content, 9.20 kg/liter (34.87 kg/gal) for 20% oil content, and 18.40 kg/liter (69.74 kg/gal) for 10% oil content. This holds true under the assumptions of this analysis regardless of the level of total target oil scale-up or level of algal oil productivity per unit of cultivation area for the simple reason that the CO_2 use intensity scales in proportion to the level of biomass produced. The relative CO_2 requirement per volume of oil produced will then simply scale inversely as the percentage of oil content, which shows that increasing biomass oil content will result in reduced CO_2 demand per volume of oil produced. From an economic perspective, the availability of concentrated CO_2 (e.g., from stationary industrial sources like fossil-fired power plants, fermentation plants, etc.) that can be used to enhance algal biomass growth, while also being located closely enough for affordable capture and transport, is a challenge for scale-up [6].

Summary for N & P:

The elemental N requirement estimates given in Table-2 to produce the minimum algal oil scale-up production target of 19 BLY (5 BGY) ranges from a low of 3.07 million metric tons at 50% oil content to a high of 15.4 million metric tons at 10% oil content, regardless of the assumed level of algal oil productivity P_L. The N required to produce the maximum algal oil scale-up production target of 190 BLY (50 BGY) is an order of magnitude higher, ranging from a low of 30.7 million metric tons at 50% oil content to a high of 153 million metric tons at 10% oil content. As a reference point, 7 million metric tons represents roughly 50% of the total elemental N, in the form of ammonia, used in the U.S. for agricultural fertilizer [7].

Similarly, the estimated elemental P requirement to produce the minimum algal oil scale-up production target of 19 BLY (5 BGY) ranges from a low of 0.42 million metric tons at 50% oil content to a high of 2.09 million metric tons at 10% oil content, regardless of the assumed level of algal oil productivity P_L. The P required to produce the maximum algal oil scale-up production target of 190 BLY (50 BGY) is an order of magnitude higher, ranging from a low of 4.18 million metric tons at 50% oil content to a high of 20.9 million metric tons at 10% oil content. As a reference point, 2 million metric tons represents roughly 50% of the total elemental P, in the form of phosphate rock, used in the U.S. for agricultural fertilizer [7].

The resulting N use intensity spans the range of: 0.162 kg/liter (0.614 kg/gal) for 50% biomass oil content, 0.231 kg/liter (0.877 kg/gal) for 35% biomass oil content, 0.405 kg/liter (1.53 kg/gal) for 20% biomass oil content, and 0.810 kg/liter (3.07 kg/gal) for 10% biomass oil content. Similarly, the resulting P use intensity spans the range of: 0.022 kg/liter (0.0837 kg/gal) for 50% biomass oil content, 0.032kg/liter (0.120 kg/gal) for 35% biomass oil content, 0.055 kg/liter (0.209 kg/gal) for 20% biomass oil content, and 0.011 kg/liter (0.042 kg/gal) for 10% biomass oil content. As with CO_2, the N and P use intensity dependence on only the oil content holds true for this analysis regardless of the level of total target oil scale-up or level of algal oil productivity per unit of cultivation area for the simple reason that the nutrient use intensity for both N and P scale in proportion to the level of biomass produced. Again as with CO_2, the relative nutrient requirement per volume of oil produced will simply scale inversely as the percentage of oil content, with increasing biomass oil content resulting in reduced nutrient demand per volume of oil produced.

More refined estimates of water and nutrient requirements will be dependent on the degree to which nutrients and water from wastewater sources can be utilized, and the capture and recycling of both nutrients and water may be possible. This assessment ignores possible recycling. The justification is that the assumed use of open algae cultivation systems will result in evaporative loss being the major water demand, with other water use relatively small in comparison. Estimating gross nutrient demand without assuming any recycling also provides a baseline assessment representing the case where all non-fuel algal biomass residue (including the nutrient content) is used for co-products that prevent recycling upstream for algae cultivation. Possibly significant water gain directly into open cultivation systems through precipitation is also ignored, but could be accounted for in any given location by interpreting the assumed gross water loss rates as net loss. Similarly, accounting for recycled water and nutrients from downstream processes at any given location can be approximately done by offsetting their contribution to the gross water and nutrient demand estimates presented here.

Algal Biomass Utilization and Carbon Offset from Stationary Emission Sources

Utilization of CO_2 from industrial emitter sources is often cited as a promising way to meet the large carbon requirements for photosynthetic algal biomass production while potentially reducing net greenhouse gas emissions [17-21]. Putting cost concerns aside, there are resource requirement issues associated with effectively matching CO_2 emissions from industrial sources for efficient utilization in algae production while generating carbon offsets. A simplified illustration of the CO_2 mass flows and utilization by algae assumed in this discussion is shown in Figure 4, with parameter definitions and functional relationships given by the Eq 6 - Eq 13 in Table-1. Results of the scenarios described below are summarized in Table-3. We begin with the earlier assumption that all of the carbon in the algal biomass comes from the photosynthetic utilization of CO_2 supplied from a stationary source like a fossil-fired power plant. The effective sunlight hours and solar energy delivery per day at any given algae cultivation site will vary as a function of latitude, elevation, and season (continuous variation as a function of day of the year), and will also be modulated by atmospheric and weather conditions such as dust and aerosol content and cloud cover. Also directly affecting the dynamics of algae growth and metabolism, and subsequent rate of inorganic carbon uptake during photosynthesis, will be the local ambient temperature of the culture. These details are neglected here by simply assuming an annual average daily algal biomass productivity, P_{BD}, as described earlier and shown in Eq 1 of Table-1. Also assumed here for simplicity is that the effective annual average daily sunlight period when photosynthesis is significantly active will be 8-hours, or one third of the 24-hour day. The rate of CO_2 emissions from fossil-fired power plants will vary with the type of plant technology and type of fuel used.

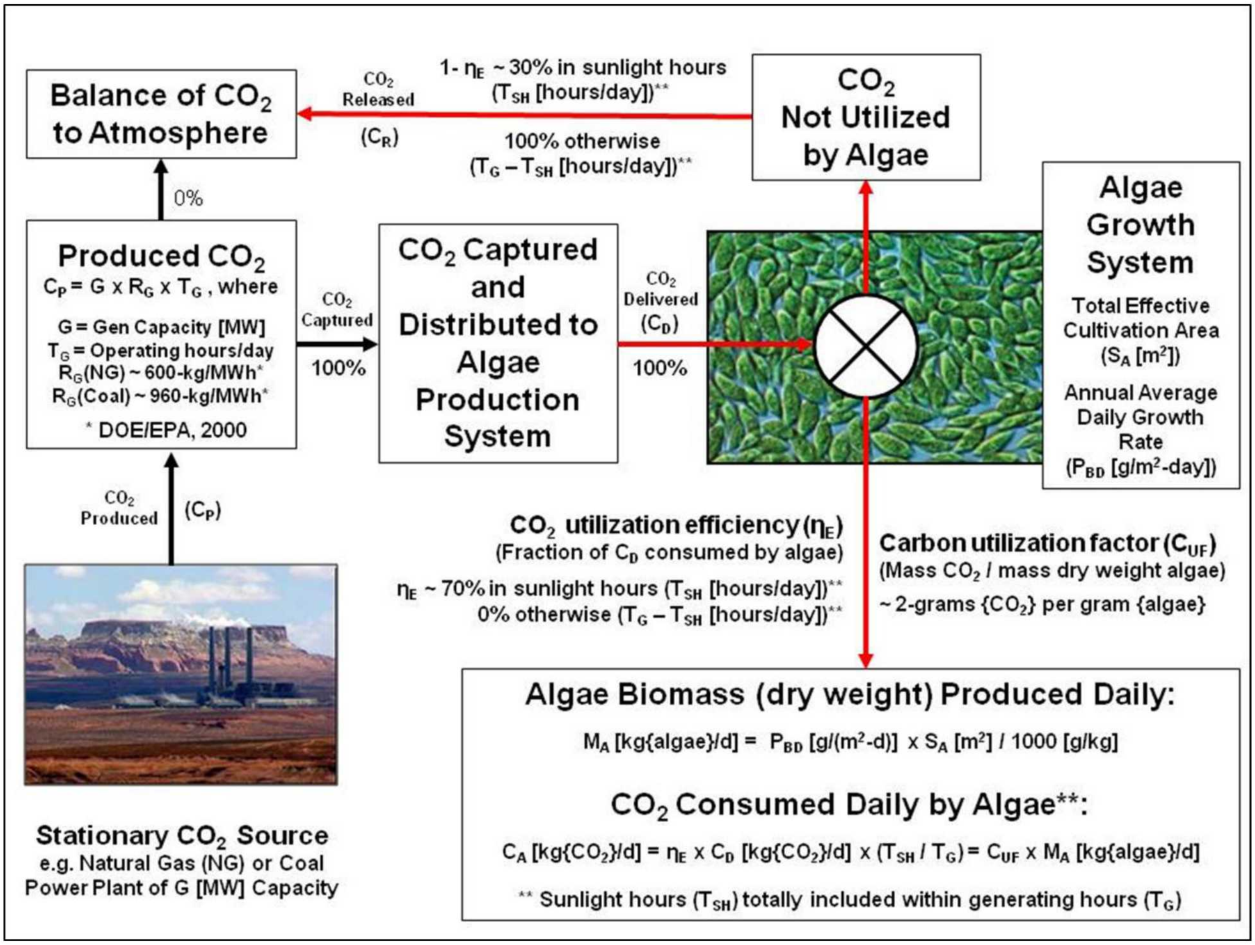


Figure 4. Notional process diagram and assumptions used for the analysis of utilization of CO_2 from stationary emission sources, such as fossil-fired power plants, as the dominant source for supporting the inorganic carbon demand for autotrophic algae production.

The average CO_2 emissions assumed for this analysis are 600-kg of CO_2 per megawatt-hour (MWh) of power plant operation using natural gas (NG) and 960 kg of CO_2 per MWh for coal. The assumption is made that the carbon utilization factor C_{UF} [g{CO_2}/g{algae}] ≈ 2 as shown earlier in Figure-2. Using these assumptions and Eq-6 through Eq-13 summarized in Table-1, rough estimates can be made for CO_2 uptake and carbon emissions offset that could result from algae biomass production. In both Table-1 and Figure-4, the notation kg{CO_2} denotes mass units (kilograms) of CO_2, as distinguished from kg{algae}, which denotes mass units of algae (AFDW). Some fraction of the CO_2 emitted from the power plant source, C_P, is assumed to be captured and delivered (C_D) to the algae cultivation system. For simplicity, 100% efficiency is assumed for this step, giving $C_D = C_P$, as shown in Eq 6 of Table-1.

The process of CO_2 bio-fixation takes place during effective sunlight hours, denoted as T_{SH}, when photosynthesis is active. The assumption is made that only that portion of C_D provided to the algae during sunlight hours can be effectively captured and incorporated into the algal biomass. The efficiency by which the CO_2 delivered to the algae system (C_D) will actually be utilized and converted to biomass is the "CO_2 utilization efficiency", designated as η_E. Efficiencies in excess of 90% have been reported [15, 17, 18], but are more likely to fall in the range of 50 - 90% in practice with large scale systems under varying operational conditions [19]. The remaining fraction of CO_2 not taken up by the algae will be released (C_R) into the environment, unless other capture and storage measures are taken. The effective illuminated surface area (S_A) of the algae cultivation system and the annual average daily biomass productivity levels achieved (P_{BD}) are assumed to be scaled to be in balance with the daily quantity of CO_2 delivered (C_D) such that the resulting CO_2 utilization efficiency (η_E) has an annual average daily value of 70% during the effective sunlight hours (T_{SH}). The sunlight hours (T_{SH}) are also assumed to be totally contained within the power plant operating hours (T_G). Any CO_2 delivered during non-sunlight hours (T_G-T_{SH}) is assumed to be totally lost to the environment ($C_R/C_D = 1$). Ignored in this idealized analysis are the details of cultivation system design, mixing, manner in which CO_2 is distributed and injected into the system, the culture media chemistry and buffering effects [15], and dynamic changes in growing conditions, all of which will affect CO_2 use efficiency and can also result in the loss of excess CO_2 delivered during daylight hours that the algae is unable to capture and utilize. Given these simplifying assumptions, the annual average daily CO_2 utilized and consumed by the algae (C_A) can be expressed by Eq 7 in Table-1. Assuming 365 days per year operation, the estimated annual average CO_2 production by the power plant (C_{PA}), the annual average algae biomass production (M_{AA}), and the annual average CO_2 consumption by the algae (C_{AA}) are determined by Eq 10-12 of Table-1. The gross carbon offset factor (G_{CO}) is defined as the fraction of CO_2 produced by the power plant (C_{PA}) that is actually consumed by the algae (C_{AA}), as shown in Eq 13 of Table-1.

Table 3 provides estimates for the algae cultivation area (S_A) required to consume C_{AA} metric tons of CO_2 annually to provide 70% utilization of the total annual CO_2 produced from a power plant (C_{PA}) for three different generation Scenarios: A) a 50-MW natural gas (NG) peaking plant operating with annual average T_G = 8-h/d coinciding with the annual average sunlight hours (T_{SH}); B) the same 50-MW NG plant in semi-base-load operation at T_G = 18-h/d that includes the annual average sunlight hours T_{SH}; and C) a 1000-MW coal-fired base-load plant operating at T_G = 24 h/d. As shown in Figure-3, the algae cultivation area required to balance the algal biomass productivity scales directly with the quantity of CO_2 delivered during sunlight hours, and scales inversely with the level of assumed algal productivity that can be achieved.

In going from Scenario-A to Scenario-B, the impact of extending generator operation beyond the period of available sun hours (T_{SH}) results in a lower percentage of CO_2 offset that can be provided by the algae biomass production. The rate of CO_2 production from coal-fired power plants is a factor of 1.6 greater than for natural gas, and the effect of moving to the larger plant capacities and 24 hour per day operations of typical coal-fired base-load plants results in significantly more CO_2 production, as shown in Table 3 for Scenario-C. The result is much larger algae cultivation acreage required to achieve the targeted 70% utilization efficiency (η_E) for a given level of annual average daily biomass productivity (P_{BD}) assumed. Gross carbon emissions offset (G_{CO}) scales as the product of the utilization efficiency (η_E) and the ratio of photosynthetically-active sunlight hours to total power generator operating hours (T_{SH}/T_G).

Table 3 further shows that this factor drops from 70% for the case of Scenario-A to 31% for the case of Scenario-B to 23% for the case of Scenario-C. Maximum carbon emissions offset is achieved by having the hours of generator operation coincide with the active sunlight hours, which maximizes the fraction of generated CO_2 that can be captured by the algae. As the time duration of daily generator operation extends beyond effective sunlight hours, the fraction of generated CO_2 that can be captured by the algae declines, and reaches a minimum with 24-h/d base-load operations. The general trends noted here are consistent with the findings of Brune, et al. [19]. A key point is that the effectiveness with which carbon emissions from stationary sources can be utilized for algae production will depend on the dynamic (time and process dependent) interaction of numerous factors, which include matching the annual average daily algae productivity and cultivation area to the volume and timing of daily emissions that can be captured. Numerous dynamic interactions involving the rate of supply of CO_2 with algae growth media pH and carbon buffering capacity, algae growth rates and carbon uptake, temperature and solar insolation conditions, and other complexities will come into play in practice [15], but the overall results and trends of this simple analysis provide a bounding approximation. Note that the algae productivities and cultivation areas shown in Table 3 have been scaled and aligned to maximize the capture of daylight hour power plant CO_2 emissions for each of the scenarios. This is unlikely to be accomplished in actual practice, resulting in the biomass produced and the gross CO_2 offset achieved being less than the values shown in the table. For example, if the cultivation area of 519 acres shown in Scenario-A and Scenario-B of Table 3 was actually associated with a lower annual average daily algal biomass productivity of 20 g m^{-2} d^{-1} instead of the 40 g m^{-2} d^{-1} assumed in the table, the result would be a factor of two reduction in the algae biomass produced, CO_2 emissions consumed by the algae, and gross CO_2 offset achieved. Another key point to be made is that the amount of CO_2 that can actually be captured and converted into algal biomass will likely be considerably less than 100% of that emitted from the source, and the cultivation area required to maximize this capture can be extremely large, depending on the rate and quantity of source emissions and the level of algae productivity that can be realistically achieved in practice. Pipeline transport and distribution infrastructure will also be required to move the captured CO_2 from the stationary emission source location to the algae cultivation site(s), especially given the land area required to grow the algae. The costs, energy, and material inputs required for such CO_2 transport and distribution within what could be very large cultivation areas will necessarily limit the practical

Table 3. Algae cultivation area required to consume CO_2 generated during daylight hours by fossil-fired power plants: A) 50-MW NG peaking plant operating 8-hours per day during sunlight; B) 50-MW NG semi-baseload plant operating 18-hours per day spanning sunlight hours; and C) 1000-MW coal fired baseload plant operating 24 h/d.

Daily Algae Productivity (P_{BD}) [1] [g/(m^2-day)]	Annual CO_2 production (C_{PA}) [2] [mt/yr]	Annual CO_2 used by algae (C_{AA}) [3] [mt/yr]	Algae biomass production (M_{AA}) [1,3,4] [mt/yr]	Algae Area Needed (S_A) [3,4] [ha]	Gross CO_2 Offset (C_{AA}/C_{PA}) [5,6] [%]
A) Natural Gas Fired Peaking Power Plant: 50-MW operating T_G = 8-hours/day [6]					
10	**87,600**	**61,440**	**30,720**	**840**	**70**
20				**420**	
30				**280**	
40				**210**	
50				**168**	
60				**140**	
B) Natural Gas Fired Semi-Baseload Power Plant: 50-MW operating T_G = 18-h/d [6]					
10	**197,100**	**61,440**	**30,720**	**840**	**31**
20				**420**	
30				**280**	
40				**210**	
50				**168**	
60				**140**	
C) Coal-Fired Baseload Power Plant: 1000-MW operating T_G = 24-h/d					
10	**8,409,600**	**1,966,080**	**983,040**	**26896**	**23**
20				**13448**	
30				**8965**	
40				**6724**	
50				**5379**	
60				**4483**	

[1] *Assuming annual average daily productivities and operation 365 days per year*
[2] *Based on assumed CO_2 production rates of 600-kg/MWh for NG and 960-kg/MWh for coal*
[3] *Based on annual average daily sun hours of T_{SH} = 8-h/d and 70% CO_2 utilization efficiency*
[4] *Based on assumed carbon utilization factor of 2-g of CO_2 per gram algae biomass (AFDW) produced*
[5] *Does not include offsets for products and fuels generated from the algae biomass produced*
[6] *Time of operation (T_G) assumed to totally include the photo-synthetically active sun hours (T_{SH})*

range for which positive energy balance and good techno-economic and life cycle performance can be achieved for the resulting algal biofuels production [4, 6, 14, 22]. The same general issues and constraints will also apply to the supply, transport, distribution, and pumped circulation of water resources needed for algae cultivation operations. Energy and water are closely-coupled in algae biofuel production, as noted in Figure-1, which demands that close attention be paid to the life cycle analysis performance details for any proposed system approach [4, 23].

Conclusions and future prospects for sustainable algae biofuels scale-up

Algae continue to hold promise as a feedstock for advanced biofuels, but production scale-up to the regional, national, and global levels needed for fuels still faces numerous technical, economic, and resource demand challenges. Requirements for land, water, carbon, and other major nutrients can be expected to impose constraints on the level to which algal biofuel production can sustainably scale. However, the requirements for resources also remain subject to uncertainty due to remaining gaps in understanding and data pertaining to algae growth, systems performance, and resource utilization at large production scales with integrated operations. As an example, conclusions from the 2012 U.S. National Academy of Sciences study on the sustainable development of algae biofuels [5] suggest that algal biofuel production scale-up in the U.S. to levels needed to meet about 5% (approximately 39 BLY, or 10 BGY) of U.S. fuel demand would place unsustainable requirements on energy, water, and nutrients based on the assumptions used. However, the report also noted that biological and engineering improvements may be possible that could reduce these constraints [5]. The future outlook for algal biofuels depends on the success of industry and the broader R&D community in overcoming logistical, technical, and economic performance challenges for the reliable, affordable, and sustainable production of algal biomass and fuels at large scale. Additional key factors will be the future availability and cost of other competing fuels, along with the policy and regulatory conditions that exist which could either help promote or impede the development of advanced biofuels from algae.

Financial & competing interests disclosure and acknowledgements

Ronald C. Pate is a Principal Member of Technical Staff at Sandia National Laboratories. He is based in Albuquerque, New Mexico pursuing research and development in the national interest the areas of Earth Systems Analysis and Energy Technologies and System Solutions. The author contributed to the development of the National Algal Biofuels Technology Roadmap process that began in 2008, and spent two years from November 2009 through September 2011 in a temporary assignment supporting the algae biofuels program of what is now the Bioenergy Technologies Office (BETO, formerly the Office of Biomass Program: OBP) at the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (DOE/EERE) in Washington, DC. He is also serving as the Deputy Director of the U.S. DOE's national algae biofuels technology test bed consortium project (Algae Testbed Public-Private Partnership: ATP^3), which is a multi-year effort in the U.S. that began in FY13 with funding from BETO under the lead of Arizona State University (ASU). The views expressed in this paper should not be considered as reflecting the view of the U.S. DOE, Sandia National Laboratories, ASU, or the ATP^3. The author has no other relevant affiliations or personal financial involvement with any organization or entity with a financial interest in, or financial conflict with, the subject matter and materials discussed in the manuscript. No writing assistance was utilized in the production of this manuscript.

Summary

Land, water, and nutrient (C, N, P) resource demand relationships and challenges for algae

- Land resource requirements scale inversely with algal biomass & oil productivity levels achieved, and scale directly with desired biomass feedstock & fuel production volumes;
- Key nutrient requirements (C, N, P) scale in proportion to average stoichiometric elemental content and C:N:P ratios of the algae biomass, nutrient uptake efficiency of the cultivation system and algae growth kinetics, levels of biomass productivity and production volumes, and degree of nutrient capturing and recycling possible from downstream processes; Uncertainty exists and needs work to better understand the C:N:P ratios in algae;
- Water use intensity will scale in proportion to cultivation area and volume, inversely with algae biomass and oil productivity, and will depend on system configuration (open vs. closed cultivation), local climate, evaporative losses, and degree of water capture & recycling that can be implemented from downstream processes;
- Land demands likely to be least restrictive & likely to accommodate large algae production scale-up;
- Water demands with algae production scale-up, especially based on fresh water resources, ~~based~~ may encounter constraints, depending on location, cultivation system approach, and local source water used (fresh, wastewater, brackish, saline);
- Nutrient (C, N, P) demands with algae production scale-up will likely encounter greatest constraints in the availability and access cost of concentrated CO_2 from stationary industrial sources, while demand for N & P from commercial fertilizer supplies will begin to compete with conventional agriculture at large biofuel volumes;
- Development or discovery of nitrogen-fixing algae, use of nutrients from municipal and agricultural wastewaters, and implementation of nutrient capture and recycled use can help reduce nutrient-related constraints.

Future for algal biofuels within the broader energy-water-land-climate nexus

- Commercialization and industry build-up will depend on future success in increasing biological, techno-economic, and life cycle system performance and reducing costs at scale relative to petroleum fuels;
- Levels of sustainable industry scale-up will depend on, and be limited by, demand and use of key resources.

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