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Life-cycle Analysis of Energy Use, Greenhouse Gas Emissions, and Water Consumption in the 2016 MYPP Algal Biofuel Scenarios

Energy Systems Division

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1 INTRODUCTION

The Department of Energy (DOE) Bioenergy Technologies Office (BETO) Multi-year Program Plan (MYPP) describes the bioenergy objectives pursued by BETO, the strategies for achieving those objectives, the current state of technology (SOT), and a number of design cases that explore cost and operational performance required to advance the SOT towards middle and long term goals (MYPP, 2016).

Two options for converting algae to biofuel intermediates were considered in the MYPP, namely algal biofuel production via lipid extraction and algal biofuel production by thermal processing. The first option, lipid extraction, is represented by the Combined Algae Processing (CAP) pathway in which algae are hydrolyzed in a weak acid pretreatment step. The treated slurry is fermented for ethanol production from sugars. The fermentation stillage contains most of the lipids from the original biomass, which are recovered through wet solvent extraction. The process residuals after lipid extraction, which contain much of the original mass of amino acids and proteins, are directed to anaerobic digestion (AD) for biogas production and recycle of N and P nutrients. The second option, thermal processing, comprises direct hydrothermal liquefaction (HTL) of the wet biomass, separation of aqueous, gas, and oil phases, and treatment of the aqueous phase with catalytic hydrothermal gasification (CHG) to produce biogas and to recover N and P nutrients.

The MYPP describes three scenarios for each of the two conversion approaches:

- **2015 SOT:** The 2015 SOT uses productivities reported by the Algae Test Bed Public-Private Partnership (ATP^3) collaboration plus biomass growth, harvesting and dewatering operations described in the 2016 “Farm Report” (Davis et al., 2016).

- **Original 2022 Target:** The Original 2022 Target scenario uses the biomass growth, harvesting, and dewatering process described in the “Harmonization Report” (Davis et al., 2012), but with forward looking assumptions for biomass productivity (30 $g/m^2/d$, annual average) and total cost.

- **Revised 2022 Target:** The Revised 2022 Target uses the Farm report biomass model (Davis et al., 2016) with biomass productivity of 25 $g/m^2/d$, annual average.

The present report describes a life cycle analysis of energy use and greenhouse gas (GHG) emissions of the CAP and HTL options for the three scenarios just described. Water use is also reported. Water use during algal biofuel production comes from evaporation during cultivation, discharge to bleed streams to control pond salinity (“blowdown”), and from use during preprocessing and upgrading. For scenarios considered to date, most water use was from evaporation and, secondarily, from bleed streams. Other use was relatively small at the level of fidelity being modeled now.

Pacific Northwest National Laboratory (PNNL) computed net evaporative loss in its Biomass Assessment Tool (BAT) model and also determined the salinity of the source water for candidate cultivation sites throughout the US (Wigmosta et al., 2011; Venteris et al., 2013). Here, net evaporative loss was the loss after considering gains from rainfall into the pond with gains limited by freeboard. The net evaporative loss rate depended upon climate and pond salinity. The bleed rate depended only upon the net evaporative loss rate, the input salinity, and the desired operating salinity, which was 4 mg/L in BAT. Neither *rate* depended upon the productivity, and was expressed in $L/m^2/d$. Because the final water consumption result is presented on the basis of fuel produced, a result giving liters of water per MJ of fuel depends upon the productivity. This occurs because the productivity determines the residence time of a quantity of algae in the pond and the residence time, in combination with the (productivity independent) evaporation rate, determines the total water evaporated while producing the biomass required for one MJ of fuel. Life-cycle analysis methods are required for the algae preprocessing and upgrading operations in order to account for water use associated with off-site activities, e.g., water use during electricity generation.

2 METHODS

The CAP and HTL pathway descriptions and assumptions will not be repeated here. See MYPP (2016) for the assumptions in the 2015 SOT and the Revised 2022 Target scenarios. The Original 2022 Target scenarios were described in (Davis et al., 2014a) (CAP) and in (Jones et al., 2014) (HTL). The 2016 Farm Report (Davis et al., 2016) describes many cultivation scenarios. See the MYPP (2016) report for details of the cultivation assumptions that were selected from the Farm Report. An LCA of energy use and GHG emissions in the CAP pathway for the Original 2022 Target is in the literature (Pegallapati and Frank, 2016).

Davis and Markham (2016) and Davis et al. (2014a) provided energy and material inventories for the CAP process while Jones and Zhu (2016) and Jones et al. (2014) provided energy and material balances for the HTL pathway (private communications). The inventories are summarized in Tables A1-A8. These material and energy balances were entered into the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) LCA tool (GREET, 2015) for analysis of energy use and GHG emissions. The material and energy balances included all recycle loops, co-generation, heat integration, and waste treatment. The energy inputs computed by the Aspen model were broken down into individual fuels (electricity and natural gas) for input into the GREET LCA model. Within GREET, the set of operations was expanded to include nutrient manufacturing (Johnson et al., 2013), biomass growth and dewatering, transportation of fuels to bulk terminal via barge, rail and truck, transportation from the bulk terminal to the fueling station by truck, and fuel use in vehicles. These operations, plus the transportation and use of AD digestate in fields as fertilizer, define the system boundary for the present LCA analysis. Details can be found in Davis et al. (2012) and Frank et al. (2011). The system boundary is consistent with other GREET transportation fuel analyses.

To simplify the analysis and to avoid technical questions regarding allocation methods, the heating values of the RD, ethanol, and naphtha were combined into a total fuel, which is referred to here as “RD equivalent” (RD_e). The flow of RD equivalent (MJ/hr) is equal to the sum, $C_{RD}\, \dot{m}_{RD} / \rho_{RD} + C_E\, \dot{m}_E / \rho_E + C_N\, \dot{m}_N / \rho_N$ where C is the heating value (MJ/L), $\dot{m}$ is the mass flow rate (Kg/hr), and ρ is the density (Kg/L) and where the subscripts indicate the various fuels (RD=renewable diesel, E=ethanol, and N=naphtha). Whenever fuel mass was required in the analysis, the total heating value of the produced fuels was divided by the heating value of RD (MJ/kg) to obtain an equivalent weight. To be consistent with the underlying techno-economic analyses, RD_e was computed with the higher heating value (HHV) for the CAP scnearios and with the lower heating value (LHV) for the HTL scenarios. Fuel properties are shown in Tables A9 and A10. (To be clear, in all cases, the *functional unit* for the analysis is 1 MJ of RD_e on an LHV basis).

Nutrients required additional consideration for the HTL scenarios. The biomass production inventories (Farm Model and Harmonization model) had nutrient demands set to match the biomass composition assumed in the CAP studies. The HTL studies, however, used experimental data for HTL treatment of specific biomass strains. See Table 1. Therefore, the Farm Model nutrient demands were replaced with the net nutrient demand, computed as the

TABLE 1 HTL Biomass Ultimate Analysis From (Jones et al., 2014; Jones, 2016)

	2015 SOT	2022 Original Target and Revised Target
C	38.60%	52%
H	5.30%	7.50%
O	27.50%	22%
N	5.00%	4.80%
S	1.60%	0.60%
Ash	22.00%	13%
P	0.40%	0.60%
Total	100.40%	100.50%

difference between the N and P levels in each HTL strain and the recycled N and P as specified by the PNNL conversion model.

In four cases, the Farm Model specified supercritical CO_2 ($scCO_2$) for transporting CO_2 to site, while in two other cases short-distance low-pressure pipeline delivery of flue gas with 20 wt% CO_2 was specified. Separation of CO_2 from coal-fired power plant flue gas via monoethanolamine (MEA) absorption requires heat to release the captured CO_2. Heat integration with the power plant steam cycles is the most energy efficient way to obtain heat for MEA recovery, but reduces the electrical efficiency of the power plant. Thus, additional fuel must be consumed to maintain the base power plant output. In the scenarios considered here, in which CO_2 was captured solely for the purpose of growing algae, the additional fuel consumption would not occur but for the production of algae. Therefore, the carbon associated with the additional fuel demand (increased heat rate) was burdened to the algal biofuel and co-products. Discussions with The National Renewable Energy Laboratory (NREL) concerning the CO_2 capture process assumed in the Farm Model established that each kilogram of $scCO_2$ increased the heat rate of the power plant by an amount that otherwise would have generated 0.635 MJ of electricity. This value represents an average over several studies in the literature (Davis et al., 2016). The emissions associated with the inflated heat rate at a coal-fired power plant were added to the LCA GHG emissions and energy use tallies.

The 2013 Harmonization report (Davis et al 2014b) considered five so-called representative sites, each of which had productivity and resource consumption that was typical for the surrounding geographical region. In the present study, evaporation and blowdown at each representative site were scaled by the ratio of the scenario productivity divided by the harmonization productivity. This ratio is equal to the ratio of residence times and thus scales the water use by the residence time in each scenario. This computation was performed for each of the representative sites and, in addition, was performed using the average productivity, evaporation, and blowdown for the ensemble of 2013 Harmonization sites. The average is the simple ensemble average, not weighted by fuel. Results are in Table 2.

TABLE 2 2013 Harmonization Productivity and Direct Water Use During Cultivation for the 2015 SOT, Original 2022 Target, and Revised 2022 Target Scenarios Obtained by Productivity-scaling. Productivity ("Prod"): annual average, g/m^2/d; Evaporative loss ("Evap"): Annual average, L/kg algae; Blowdown ("Bldn"): Annual average, L/kg algae. Algae weight is gross algae, before harvest efficiency, on a dry ash free basis.

	2013 Harmonization			2015 SOT			Original 2022 Target			Revised 2022 Target		
Location	Prod g/m^2/d	Evap L/kg	Bldn L/kg	Prod g/m^2/d	Evap L/kg	Bldn L/kg	Prod g/m^2/d	Evap L/kg	Bldn L/kg	Prod g/m^2/d	Evap L/kg	Bldn L/kg
Representative Site 1	13.5	205	133	8.5	325	211	30	92	60	25	111	72
Representative Site 2	13.6	116	16	8.5	186	26	30	53	7	25	63	9
Representative Site 3	12.9	73	13	8.5	111	19	30	31	5	25	38	7
Representative Site 7	14.2	40	7	8.5	66	11	30	19	3	25	23	4
Representative Site 8	15.1	29	2	8.5	52	4	30	15	1	25	18	1
Ensemble average	14.6	60	21	8.5	103	36	30	29	10	25	35	12

To obtain water use on the basis of net produced fuel, the harvest efficiency and fuel yield values were required as were the preprocessing and upgrading water-use numbers. These values were obtained from the NREL and PNNL studies of the CAP and HTL processes. See Table 3. These values were added to GREET and were used to obtain total water use on a life-cycle basis. The CAP process assumed that AD digestate was sold as a wet soil amendment (30 wt% solids). Water in the digestate was added to the water demand sum because the water will evaporate from the field and will not directly return to the source. Water incorporated in the digestate will be at the pond salinity at the time of harvest, but will be replaced by water at the source salinity. This difference in salinity was not accounted for in the pond salt balance contained in the 2013 numbers. The digestate water was small compared to evaporative and blowdown losses, so this omission will not affect the results significantly.

TABLE 3 Direct Water Consumption During Algae Biomass Preprocessing and Upgrading. Process water is net consumed water.

	CAP 2015 SOT		CAP Original 2022 Target		CAP Revised 2022 Target	
Biomass feed	7100	kg afdw /hr	50611	kg afdw /hr	21480	kg afdw /hr
Process water	10569	kg H2O/hr	78155	kg H2O/hr	36452	kg H2O/hr
Digestate	1447	kg dw/hr	8325	kg dw/hr	3935	kg dw/hr
Water in digestate	3261	kg H2O/hr	17623	kg H2O/hr	8305	kg /hr
Water use	1.49	L H2O/kg afdw	1.54	L H2O/kg afdw	1.70	L H2O/kg afdw
Water use if water in digestate is considered to be returned to the ecosystem	1.03	L H2O/kg afdw	1.20	L H2O/kg afdw	1.31	L H2O/kg afdw
	HTL 2015 SOT		**HTL Original 2022 Target**		**HTL Revised 2022 Target**	
Biomass feed	15653	lb afdw /hr	111608	lb afdw /hr	47355	lb afdw /hr
Process water	7550	lb H2O/hr	97111	lb H2O/hr	41823	lb H2O/hr
Water use	0.482	L H2O/kg afdw	0.870	L H2O/kg afdw	0.883	L H2O/kg afdw

3 RESULTS AND DISCUSSION

Table 4 displays the energy use and GHG emissions results summed over the fuel and infrastructure cycles. Emissions and energy use associated with algal biofuel production in the FY15 SOT scenarios were comparable to those from petroleum diesel; thus, no sustainability benefit was derived in this scenario. Only the Original 2022 Target case reduced GHG emissions by at least 50%. Infrastructure cycle emissions were computed with the Harmonization Model infrastructure (Davis et al., 2012, Canter et al. 2014), even for the scenarios based on the new Farm Model. This approximation was necessary because the infrastructure cycle emissions have not been updated since the Harmonization Model. Note that the estimated infrastructure cycle emissions are only 5% to 8% of the total for the 2015 SOT and Revised 2022 Target cases, so errors resulting from this approximation should be small.

The high emissions were caused, in part, by supplying CO_2 via pure, captured CO_2. In Table 4, the FY15 SOT and Revised 2022 Target scenarios both assumed captured CO_2, but the Original 2022 Target used flue-gas delivered by short distance, low-pressure pipeline. Table 5 shows the results when the CO_2 was supplied by a short-distance flue-gas pipeline in the FY15 SOT and Revised 2022 Target cases. Changing carbon delivery from $scCO_2$ to low-pressure flue gas enables the Revised 2022 Target case to have emissions less than 50% of petroleum diesel, but the FY15 SOT case remains higher than the Renewable Fuel Standard (RFS2) requirement for advanced biofuels.

Captured CO_2 was considered in the FY15 SOT and the Revised 2022 Target cases because low-pressure flue gas can only be transported short distances (Benemann and Oswald 1996, Campbell et al. 2009, Frank et al. 2011). Unfortunately, captured CO_2 has a large energy and emissions burden because of the increase in heat rate at the power plant. The short transportation distance associated with low-pressure flue gas pipelines puts tight constraints on cultivation siting and also limits the size of the cultivation facility. The 2m-diameter flue gas pipeline in this study was 7 km long, which was the longest distance considered in Frank et al. (2011). An earlier study by Benemann and Oswald (1996) concluded that transport was limited to 2.5 to 5.0 km, with 2.5 km more likely because of pipeline costs. NREL studies (unpublished) suggest that low-pressure pipelines are limited to approximately one mile and that cost and energy use increase rapidly with pipeline length. Therefore, the conclusion that low-pressure flue gas pipelines outperform carbon capture scenarios should be understood to be limited to tight co-location of algae growth with a 20 wt% flue-gas source. Pure CO_2 sources such as metabolic CO_2 from fermentation could extend the pipeline length, but tacitly ties the algae production to terrestrial carbon production via the fermentation feedstock, e.g., corn grain, stover, or cellulosic energy crop.

Direct process energy consumption is shown in Figures 1 and 2, which illustrate that the largest difference between the scenarios is whether $scCO_2$ was used to deliver CO_2, as was already discussed. Another large effect was the lower productivity in the FY15 SOT scenarios. Low biomass productivity (8.4 $g/m^2/d$) implies long residence time in the pond, which is reflected in high energy use for algae growth because of the extended mixing time.

TABLE 4 Full Life-cycle (well to wheels) GHG Emissions and Energy Use Results. Results are the sum of the fuel cycle and infrastructure cycle values. The fuel cycle includes all operations required to produce, distribute, and use a fuel. The infrastructure cycle includes all operations associated with manufacturing the farm and biorefinery (Canter et al., 2014).

Scenario	GHG Emissions $g\ CO_2e / MJ\ RD_e$[a]	Fossil Energy Use $MJ/ MJ\ RD_e$	Petroleum Use $MJ/MJ\ RD_e$	Yield $g\ RD_e/g$ afdw[b]
Petroleum diesel	93	1.2	1.1	
FY15 SOT				
CAP	93	1.2	0.11	0.33
HTL	91	1.1	0.04	0.34
Original 2022 Target				
CAP	34	0.50	0.063	0.44
HTL	35	0.44	0.022	0.49
Revised 2022 Target				
CAP	56	0.71	0.083	0.35
HTL	51	0.62	0.027	0.48

[a] RD_e- See "Methods" section for the definition.

[b] afdw- ash free dry weight of algae

TABLE 5 Full Life-cycle (well to wheels) GHG Emissions and Energy Use Results when CO_2 was Supplied by Flue-gas Delivered by Low-pressure Pipeline Instead of Supercritical CO_2

Scenario	GHG Emissions $g\ CO_2e / MJ\ RD_e$	Fossil Energy Use $MJ/ MJ\ RD_e$	Petroleum Energy Use $MJ/MJ\ RD_e$
FY15 SOT			
CAP	75	1.0	0.11
HTL	77	1.0	0.039
Revised 2022 Target			
CAP	39	0.55	0.081
HTL	38	0.50	0.025

Within any of the three scenarios, CAP and HTL performed similarly for GHG emissions. CAP always had higher petroleum use because petroleum-derived solvents were required for the solvent extraction step. Fossil energy use was slightly higher for CAP, approximately 14%. Most of this difference is explained by the petroleum-derived solvent use.

Life cycle water use for the fuel cycle is shown in Table 6 for each of the six MYPP scenarios. The results include life-cycle water use for all activities associated with manufacturing, transporting, and using algal biofuels.

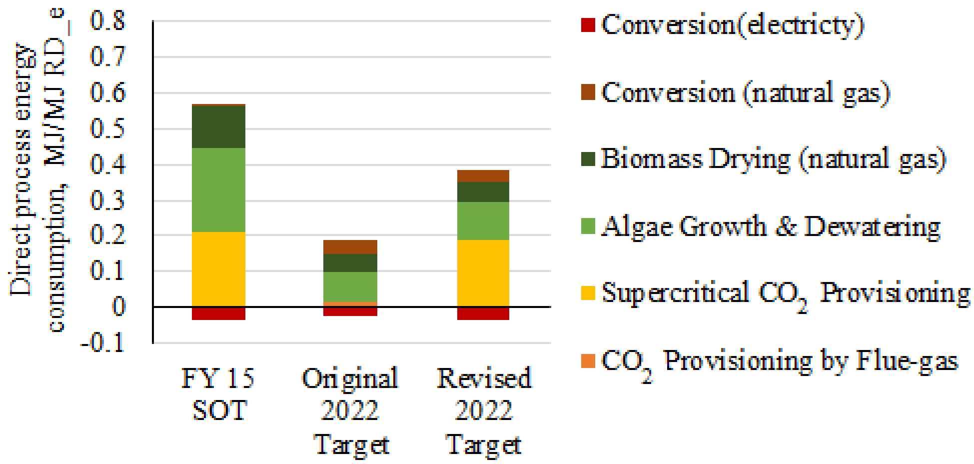

FIGURE 1 Direct Process Energy Consumption in the CAP Pathway. Natural gas demand shown is net. Note that the excess electricity from conversion (shown as a negative value) is recycled to the process, which offsets the energy use in the other units (upstream cultivation "farm" step), but grid electricity is still required, in total (when considering the net balance between cultivation farm demands and CAP conversion excess power). The electricity production is via a co-generation plant fired with biogas derived from process residuals. The co-gen operation is lumped into the conversion area.

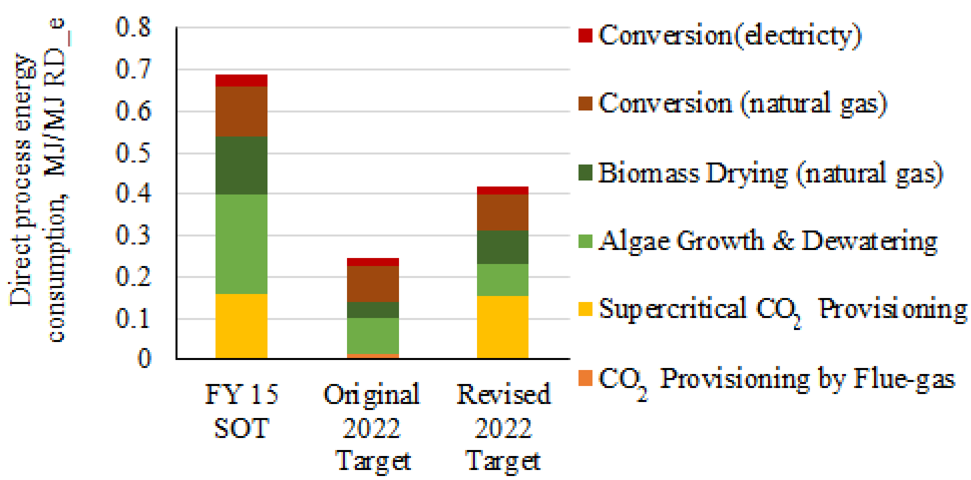

FIGURE 2 Direct Process Energy Consumption in the HTL Pathway

TABLE 6 Life-cycle Water Use for the Algae MYPP Pathways for the Five Representative Sites in the FY13 Harmonization Study and for the Site Ensemble Average

	2015 SOT		Original 2022 Target		2022 Revised Target	
	CAP	HTL	CAP	HTL	CAP	HTL
	gal H_2O / gal RD_e					
Rep. Site 1	1300	1300	290	270	400	310
Rep. Site 2	510	520	130	120	160	130
Rep. Site 3	320	320	86	81	100	80
Rep. Site 7	200	200	60	56	66	51
Rep. Site 8	140	150	49	46	50	39
Ensemble Average	340	350	90	85	110	85
	gal H_2O / GGE*					
Rep. Site 1	1200	1200	260	240	370	280
Rep. Site 2	470	470	120	110	150	110
Rep. Site 3	290	290	80	70	100	70
Rep. Site 7	180	180	50	50	60	50
Rep. Site 8	130	130	40	40	50	40
Ensemble Average	310	310	80	80	100	80

* LHVs of RD and gasoline used in computing GGE are in Tables A9 and A10.

4 CONCLUSIONS

Life cycle energy use and GHG emissions were presented for two algae to biofuel conversion pathways in the three scenarios defined in the 2016 MYPP. Use of supercritical CO_2 in the FY15 SOT and in the Revised 2022 Target cases increased the GHG emissions substantially. GHG emissions from both pathways satisfy the RFS2 criteria of advanced biofuels only when the CO_2 is supplied by low-pressure flue gas transported over short distances. In the current scenarios, one either suffers limitations on deployment scale by imposing stringent constraints on farm sizing and siting possibilities that must be co-located with CO_2 point sources (low-pressure flue gas case), or suffers high energy-use and high GHG emissions for longer-distance transport of high-pressure purified $_{CO2}$ (scCO_2 case). Note, however, that recent work by NREL indicates that low-pressure flue gas transport by pipeline is more challenging on a cost and energy basis than was estimated in the harmonization flue-gas model, used here. Carbon delivery remains a large challenge and uncertainty for algal biofuel production, and continues to be a key issue requiring further analysis for national-scale ramifications on economics and environmental sustainability.

The water usage results must be interpreted with care. First, prior reviews of the algae technology area have raised concerns about interpreting analysis results when the underlying technology is so young and when so much is not demonstrated in the field. Given the sensitivity to productivity and site location, results may only be useful for relative comparisons within algae scenarios and should not be compared with studies for other biofuels that neglect irrigation requirements.

The geographical variation in water use must be interpreted carefully. The BAT biomass productivity and water use data from the underlying harmonization study were calculated site by site using 30-years of local hourly meteorological data to drive a mass and energy-balance pond model to estimate water temperature and evaporation that was combined with a biophysical productivity model. The MYPP scenarios are quite the opposite and involve fixed, *hypothetical* productivities that were imposed on each site without consideration of the site conditions and regardless of estimated strain performance at a specific location. Thus, water consumption results in Table 6 must be interpreted with care and are to be understood as the water consumption at a given site *if* the hypothetical productivity that defines the MYPP scenario were to be achieved there or, for the ensemble average, *if* the MYPP scenario productivity were to be achieved on average over all sites. Results are best understood as a test of the variability in water demand in the Gulf region. The results are based upon 30-year averages of daily water use and convey only site-to-site variability. Inter-annual variability was not assessed.

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APPENDIX

TABLE A1 Farm Model Parameters for the FY15 SOT Case

Materials and Energy inputs, Units	Value
Net CO_2 demand , g CO_2/g afdw* algae	2.29E+00
Ammonia, g/g afdw algae	2.35E-02
Diammonium Phosphate, g/g afdw algae	1.18E-02
Total process water input, g/g afdw algae	9.44E+01
Electricity demand, kWh/g afdw algae	9.61E-04
Products, Units	
Algal biomass (afdw), g	1.00E+00
Algal biomass (total including ash), g	1.03E+00
Water in biomass product stream, g/g afdw algae	4.12E+00
Output Streams, Units	
Water lost to blowdown, g/g afdw algae	3.69E+01
Algae lost in blowdown, g/g afdw algae	1.18E-03
Supercritical CO_2 utilization efficiency in ponds	90%

*afdw-ash free dry weight of algae

TABLE A2 Farm Model Parameters for the Revised 2022 Target Case

Materials and Energy inputs, Units	Value
Net CO_2 demand , g CO_2/g afdw* algae	2.22E+00
Ammonia, g/g afdw algae	1.94E-02
Diammonium Phosphate, g/g afdw algae	9.69E-03
Total process water input, g/g afdw algae	5.19E+01
Electricity demand, kWh/g afdw algae	4.54E-04
Products, Units	
Algal biomass (afdw), g	1.00E+00
Algal biomass (total including ash), g	1.02E+00
Water in biomass product stream, g/g afdw algae	4.03E+00
Output Streams, Units	
Water lost to blowdown, g/g afdw algae	1.22E+01
Algae lost in blowdown, g/g afdw algae	6.40E-04
Supercritical CO_2 utilization efficiency in ponds	90%

*afdw-ash free dry weight of algae

TABLE A3 Parameters in the CAP Model, FY15 SOT Case

Materials and Energy inputs, Units	Value
Algae biomass, g afdw[a]/g RD_e[b]	3.03E+00
Hexane makeup, g/g RD_e	6.07E-02
Acid (pretreatment), g/g RD_e	2.67E-01
Ammonia (pretreatment), g/g RD_e	8.63E-02
DAP (ethanol fermentation), g/g RD_e	5.98E-03
Supplemental natural gas (utility), kWh/g RD_e	8.39E-05
Natural gas for summer and spring drying, kWh/g RD_e	1.43E-03
Hydrogen , g/g RD_e	3.38E-02
Process water demands, g/g RD_e	4.52E+00
Phosphoric acid (lipid purification), g/g RD_e	1.28E-03
Silica (lipid purification), g/g RD_e	8.55E-04
Clay (lipid purification), g/g RD_e	1.71E-03
Products, Units	
RD_e, g	1.00E+00
Output Streams, Units	
AD digestate (dry basis total flow), g/g RD_e	6.18E-01
AD digestate bioavailable N, g/g RD_e	4.27E-03
AD effluent NH3, g/g RD_e	4.49E-02
AD effluent DAP, g/g RD_e	1.79E-02
Recycle water excluding N/P nutrients, g/g RD_e	1.39E+01
Electricity, kWh/g RD_e (recyled to power upstream operations)	4.03E-04
CO_2 in the flue gas, g/g RD_e	1.97E+00
Intermediate Stream, Units	
AD methane, g/g RD_e	2.68E-01

[a] afdw-ash free dry weight of algae; [b]RD_e-See “Methods” section for the definition

TABLE A4 Parameters in the CAP Model, Original 2022 Target Case

Materials and Energy inputs, Units	Value
Algae biomass, g afdw[a]/g RD_e[b]	2.28E+00
Hexane makeup, g/g RD_e	4.10E-02
Acid (pretreatment), g/g RD_e e	1.01E-01
Ammonia (pretreatment), g/g RD_e	3.25E-02
DAP (ethanol fermentation), g/g RD_e	4.64E-03
Supplemental natural gas (utility), kWh/g RD_e	5.07E-04
Natural gas for summer drying, kWh/g RD_e	2.05E-03
Hydrogen , g/g RD_e	2.26E-02
Process water demands, g/g RD_e	3.52E+00
Phosphoric acid (lipid purification), g/g RD_e	1.76E-03
Silica (lipid purification), g/g RD_e	9.47E-04
Clay (lipid purification), g/g RD_e	1.85E-03
Products, Units	
RD_e, g	1.00E+00
Output Streams, Units	
AD digestate (dry basis total flow), g/g RD_e	3.75E-01
AD digestate bioavailable N, g/g RD_e	2.93E-03
AD effluent NH3, g/g RD_e	3.06E-02
AD effluent DAP, g/g RD_e	1.33E-02
Recycle water excluding N/P nutrients, g/g RD_e	1.05E+01
Electricity, kWh/g RD_e (recycled to power upstream operations)	3.11E-04
CO_2 in the flue gas, g/g RD_e	1.56E+00
Intermediate Stream, Units	
AD methane, g/g RD_e	1.26E-01

[a] afdw-ash free dry weight of algae; [b]RD_e-See "Methods" section for the definition

TABLE A5 Parameters in the CAP Model, Revised 2022 Target Case

Materials and Energy inputs, Units	Value
Algae biomass, g afdw[a]/g RD_e[b]	2.83E+00
Hexane makeup, g/g RD_e	4.34E-02
Acid (pretreatment), g/g RD_e	1.24E-01
Ammonia (pretreatment), g/g RD_e	4.03E-02
DAP (ethanol fermentation), g/g RD_e	5.39E-03
Supplemental natural gas (utility), kWh/g RD_e	4.01E-04
Natural gas for summer and spring drying, kWh/g RD_e	6.91E-04
Hydrogen , g/g RD_e	1.86E-02
Process water demands, g/g RD_e	4.80E+00
Phosphoric acid (lipid purification), g/g RD_e	1.45E-03
Silica (lipid purification), g/g RD_e	7.89E-04
Clay (lipid purification), g/g RD_e	1.58E-03
Products, Units	
RD_e, g	1.00E+00
Output Streams, Units	
AD digestate (dry basis total flow), g/g RD_e	5.18E-01
AD digestate bioavailable N, g/g RD_e	4.08E-03
AD effluent NH3, g/g RD_e	4.24E-02
AD effluent DAP, g/g RD_e	1.66E-02
Recycle water excluding N/P nutrients, g/g RD_e	1.29E+01
Electricity, kWh/g RD_e (recycled to power upstream operations)	3.97E-04
CO_2 in the flue gas, g/g RD_e	1.84E+00
Intermediate Stream, Units	
AD methane, g/g RD_e	1.97E-01

[a]afdw-ash free dry weight of algae; [b]RD_e-See “Methods” section for the definition

TABLE A6 Parameters in the HTL Model, 2015 SOT Case

Materials and Energy inputs, Units	Value
Algae biomass, g afdw[a]/g RD_e[b]	2.96E+00
Supplemental natural gas (H_2 Production), kWh/g RD_e	9.93E-04
Natural gas for summer & spring drying, kWh/g RD_e	1.73E-03
Process water demands (water consumption rate), g/g RD_e	1.43E+00
Electricity demand, kWh/g RD_e	3.65E-04
Products, Units	
RD_e, g	1.00E+00
Output Streams, Units	
P recycle, g/g RD_e	1.36E-02
N recycle, g/g RD_e	1.70E-01
CO_2 recycle in treated water (HTL and hydrotreating), g/g RD_e	2.97E-01
CO_2 in the flue gas, g/g RD_e	2.05E+00

[a] afdw-ash free dry weight of algae; [b]RD_e-See “Methods” section for the definition

TABLE A7 Parameters in the HTL model, Original 2022 Target Case

Materials and Energy inputs, Units	Value
Algae biomass, g afdw[a]/g RD_e[b]	2.06E+00
Supplemental natural gas (H_2 Production), kWh/g RD_e	8.20E-04
Natural gas for summer & spring drying, kWh/g RD_e	2.53E-03
Process water demands (water consumption rate), g/g RD_e	1.89E+00
Electricity demand, kWh/g RD_e	2.21E-04
Products, Units	
RD_e, g	1.00E+00
Output Streams, Units	
P recycle, g/g RD_e	1.42E-03
N recycle, g/g RD_e	1.01E-01
CO_2 recycle in treated water (HTL and hydrotreating), g/g RD_e	4.98E-01
CO_2 in the flue gas, g/g RD_e	1.05E+00

[a] afdw-ash free dry weight of algae; [b]RD_e-See “Methods” section for the definition

TABLE A8 Parameters in the HTL Model, Revised 2022 Target Case

Materials and Energy Inputs, Units	Value
Algae biomass, g afdw[a]/g RD_e[b]	2.06E+00
Supplemental natural gas (H_2 Production), kWh/g RD_e	8.34E-04
Natural gas for summer & spring drying, kWh/g RD_e	9.51E-04
Process water demands (water consumption rate), g/g RD_e	1.82E+00
Electricity demand, kWh/g RD_e	2.31E-04
Products, Units	
RD_e, g	1.00E+00
Output Streams, Units	
P recycle, g/g RD_e	1.27E-02
N recycle, g/g RD_e e	1.02E-01
CO_2 recycle in treated water (HTL and hydrotreating), g/g RD_e	3.77E-01
CO_2 in the flue gas, g/g RD_e	1.06E+00

[a] afdw-ash free dry weight of algae; [b]RD_e-See "Methods" section for the definition

TABLE A9 Fuel Properties Used to Define Equivalent Fuel (RD_e) in CAP Pathway

	Original 2022 Target			FY15 SOT and Revised 2022 Targets		
Fuel	LHV (MJ/L)	HHV (MJ/L)	Density (Kg/L)	LHV (MJ/L)	HHV (MJ/L)	Density (Kg/L)
RD	34.3	36.4	0.77	34.3	37.2	0.77
EtOH	21.3	23.6	0.79	21.3	23.6	0.79
Naphtha	32.6	34.9	0.73	32.6	34.6	0.73
Gasoline	31.3	33.6	0.74	31.3	33.6	0.74

TABLE A10 Fuel Properties Used to Define Equivalent Fuel (RD_e) in the HTL Pathway. The values vary by scenario, but match the underlying TEA studies

	2015 SOT		Original 2022 Target		Revised 2022 Target	
Fuel	LHV (MJ/L)	Density (Kg/L)	LHV (MJ/L)	Density (Kg/L)	LHV (MJ/L)	Density (Kg/L)
RD	34.8	0.8	34.5	0.8	34.4	0.8
Naphtha	33.1	0.77	33.9	0.79	32.6	0.76
Gasoline	31.3	0.74	31.3	0.74	31.3	0.74

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