ANL/ESD/11-7

User Manual for Algae Life-Cycle Analysis with GREET: Version 0.0

Energy Systems Division

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User Manual for Algae Life-Cycle Analysis with GREET: Version 0.0

by
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NOTATION

AD	anaerobic digestion
APD	Algae Process Description
BFP	belt filter press
C	carbon
CAPDET	Computer-Assisted Procedure for Design and Evaluation of Wastewater Treatment Systems
CH_4	methane
CHP	combined heat and power
CO_2	carbon dioxide
DAF	dissolved air flotation
EPA	U.S. Environmental Protection Agency
GPM	gallon(s) per minute
GREET	Greenhouse Gasses, Regulated Emissions, and Energy Use in Transportation (model)
HP	horsepower
IGCC	integrated gasification combined cycle
LCA	life-cycle analysis
LEA	lipid-extracted algae
LHV	lower heating value
MGD	million gallons per day
mmBTU	million Btu
N	nitrogen
NG	natural gas
NGCC	natural gas combined cycle
NH_3	ammonia
N_2O	nitrous oxide
P	phosphorus
PBR	photobioreactor
TSS	total suspended solids
wt%	weight percent

USER MANUAL FOR ALGAE LIFE-CYCLE ANALYSIS WITH THE GREET MODEL

by

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1 INTRODUCTION

The economic and environmental analysis of algae biofuel production is in its early stages. Many questions regarding energy return, emissions, and environmental sustainability are unanswered. It is difficult to compare the scenarios reported so far because of differences in the analysis methodologies and in the process data.

The Algae Process Description (APD), in combination with the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) modeling system, provides a platform for systematically exploring algae biofuel production options. The APD allows analysts to readily define an algal biofuel pathway by selecting processes from a process inventory. The expanded GREET system provides a common analysis methodology and resources that span the diverse set of fossil fuels, biofuels, engines, vehicles, and infrastructure characteristics.

The combined APD-GREET system facilitates clear, consistent, shared analysis of algal biofuel production among government, industry, academia, and other stakeholders. These tools improve the speed and efficacy of algal fuel development and enable comparison of algal biofuels with other transportation fuels (including other biofuels). Jointly, APD and GREET cover all five life-cycle stages:

1. Feedstock cultivation,
2. Feedstock transport,
3. Biofuel production,
4. Biofuel transport, and
5. Biofuel end use in vehicles.

These key stages include carbon dioxide (CO_2) transport and transfer, nutrient consumption and recycling, algae biomass harvesting and drying, oil extraction, and the conversion of oil to liquid fuel.

This document describes the life-cycle analysis (LCA) capabilities provided by GREET and APD. GREET and APD used together can analyze the emissions and energy use incurred when liquid transportation fuels are manufactured from algae. The inventory of parameterized operations in APD is used to (1) define the production pathway; (2) itemize consumed fuels and materials; (3) define unit process inputs, outputs, and yields; and (4) summarize the pathway steps for GREET. GREET then considers the conversion of lipids into fuel, material

transportation steps, co-product treatment, and emissions calculations to assess the cradle-to-grave energy use and emissions associated with algae fuel pathways.

Note: This is an experimental "alpha release." Bugs and issues are likely. We will be grateful for information that helps us improve the system, either by correcting bugs or contributing new processes to expand the system beyond this first stage.

2 APD METHODOLOGY

We collected data from the public literature, LCA inventories, government reports, conference reports, and discussions with researchers and assembled those data into the information and process inventory reported on here. Our search emphasized reports on large-scale processes, but we also frequently cite process simulations for cases in which no empirical data were available. The process inventory includes parameters for many of the processes in order to facilitate sensitivity studies. We implemented APD with an Excel spreadsheet to facilitate its distribution to researchers and its integration with GREET, which is also implemented in Excel.

2.1 SYSTEM BOUNDARY, CARBON ACCOUNTING, AND FUNCTIONAL UNIT

An Argonne technical report discusses the system boundary, carbon accounting, and functional unit employed by GREET and APD (Frank et al. 2011).

2.2 ALGAL FUEL PATHWAY ABSTRACTION

The production pathway was abstracted as shown in Figure 1. Growth and first dewatering were combined because they account for almost all water movement, even if the initial dewatering stage achieves a total solids concentration of only 1%. "Further dewatering" allows the combination of several processes—such as dissolved air flotation (DAF), belt filter press (BFP), and thermal drying—to achieve the water levels needed for extraction. Extraction includes the disruption of cellular structures and the separation of products like lipids. Conversion processes convert the extracted intermediates to fuels and co-products. Recovery accounts for processes like anaerobic digestion (AD) and power generation, which recover process wastes (including waste heat and waste CO_2 from on-site power generation) for reuse. Transport accounts for the transportation of products and intermediates (e.g., the movement of intermediates to regional centers for conversion into fuels and the movement of final products to market). Another subsystem is CO_2 transport and transfer, which parameterizes energy use during the transport of supplementary CO_2 to the algae farm and its subsequent transfer into the culture.

2.3 APD ORGANIZATION

APD is an Excel file with several worksheets. The worksheet names are "Copy to GREET," "CO_2," "Nutrients," "Growth & 1st Dewater," "Remaining Dewatering," "Extraction," and "Recovery." The worksheets correspond to the GREET process blocks shown in Figure 1, except that the GREET blocks called "Metabolite Conversion" and "Transport" are labeled "Algae" on the APD worksheets.

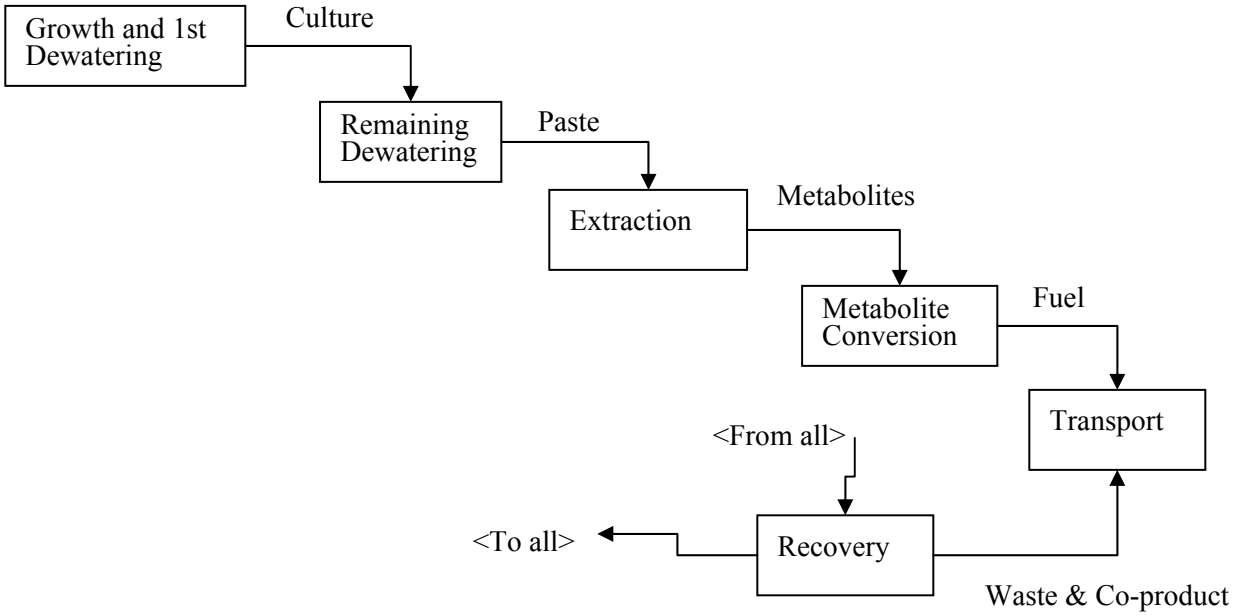


FIGURE 1 Abstracted Algal Biofuel Production Pathway ("Recovery" separates reusable materials and returns them to the process. "Transport" distributes products to market and moves intermediates between distributed processes.)

The bottom of each APD worksheet has a table of process descriptions. Each process description enumerates the direct energy and material inputs for that process. For example, Figure 2 shows a portion of the process descriptions table for the "Remaining Dewatering" worksheet. Direct inputs are the quantities of fuels and materials consumed; materials include fertilizers, solvents, acids, and other chemicals. GREET uses the direct energy inputs to compute upstream energy consumption and upstream emissions. The process description method is described in Section 2.3.1.

The middle of each worksheet includes parameters that determine the values in the process description table. The example in Figure 3 shows parameters related to centrifugation. The top of each worksheet has a process selection table that selects which processes in the process description table will actually be used in the pathway. Drop-down menus simplify the configuration work for the analyst. The example in Figure 4 shows the top of the "Remaining Dewatering" page configured to combine DAF and centrifugation to achieve the final dewatering requirements.

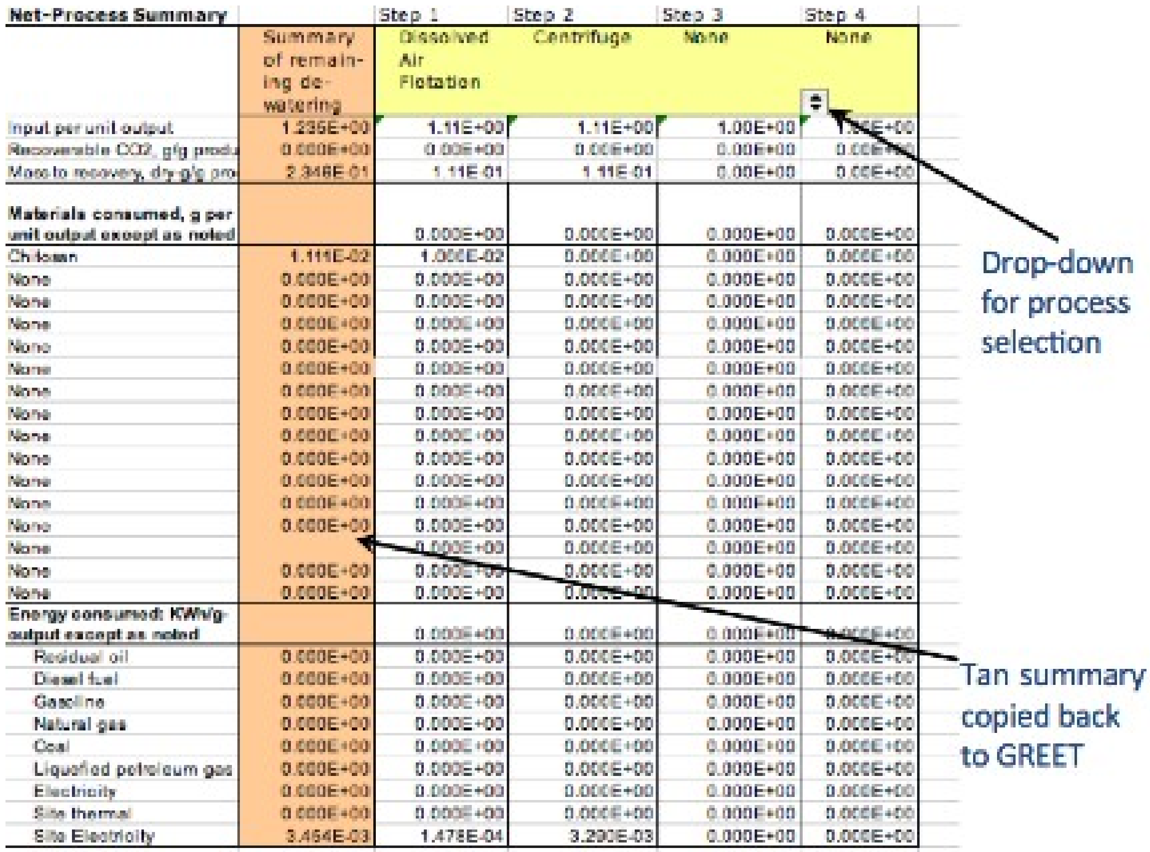
3) Calculations of Energy Consumption for each stage, KWh/g-algae except as noted

	Dissolved Air Flotation	Belt Filter press, 4% TSS input	Belt Filter press, 6% TSS input	Belt Filter press, 8% TSS input	Fournier Rotary Press
Input per unit output	1.11E+00	1.03E+00	1.03E+00	1.03E+00	1.05263158
Recoverable CO2, g/g product	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00
Mass to recovery, dry-g/g product	1.11E-01	3.09E-02	3.09E-02	3.09E-02	5.26E-02
Materials consumed, g per unit output except as noted					
Chitosan	1.000E-02				
None					
Energy consumed: KWh/g-output except as noted					
Residual oil					
Diesel fuel					
Gasoline					
Natural gas					
Coal					
Liquefied petroleum gas					
Electricity					
Site thermal					
Site Electricity	1.478E-04	1.871E-04	8.924E-05	4.153E-05	2.318E-06

FIGURE 2 Example of a Process Description Table

Centrifuge and Belt Filter Press			
Initial solids, centrifuge	10.0%		
	Energy, KWh/Kg-influent	Energy, KWh/g-algae	Recovery efficiency
Selected centrifuge values:	3.29E-03	3.29E-05	95%
1 hp/gpm centrifuge rule of thumb	3.29E-03	3.29E-05	95%
Disc-stack	1.00E-03	1.00E-05	90%
Decanter bowl	8.00E-03	8.00E-05	90%
Belt Filter Press, 4% TSS input rating	7.26E-03	1.82E-04	97%
Belt Filter Press, 6% TSS input rating	4.03E-03	6.72E-05	97%
Belt Filter Press, 8% TSS input rating	3.22E-03	4.03E-05	97%
Fournier Rotary Press	2.20E-04	2.20E-06	95%

FIGURE 3 Example of Process Parameters (In this case, they are for centrifugation from the "Remaining Dewatering" worksheet.)



Net-Process Summary	Summary of remaining de-watering	Step 1 Dissolved Air Flotation	Step 2 Centrifuge	Step 3 None	Step 4 None
Input per unit output	1.235E+00	1.11E+00	1.11E+00	1.00E+00	[illegible]
Recoverable CO2, g/g produ	0.000E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mass to recovery, dry-g/g pro	2.346E-01	1.11E-01	1.11E-01	0.00E+00	0.00E+00
Materials consumed, g per unit output except as noted		0.000E+00	0.000E+00	0.000E+00	0.000E+00
Chitosan	1.111E-02	1.000E-02	0.000E+00	0.000E+00	0.000E+00
None	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
None	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
None	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
None	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
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None	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
None	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Energy consumed: KWh/g output except as noted		0.000E+00	0.000E+00	0.000E+00	0.000E+00
Residual oil	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Diesel fuel	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Gasoline	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Natural gas	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Coal	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Liquefied petroleum gas	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Electricity	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Site thermal	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Site Electricity	3.454E-03	1.478E-04	3.290E-03	0.000E+00	0.000E+00

FIGURE 4 Example of the Configuration

2.3.1 Process Description

Each process description is composed of three blocks (Figure 5).

- Block 1 (linkage block) contains information needed to link processes into pathways.
  - *Input per unit output.* Some processes are essentially transformations that convert a principal input to a principal output. In these processes, "input per unit output" is defined by the ratio of input to output (e.g., 2 grams of CO_2 input per dry-gram of algae grown). Table 1 clarifies the meaning of this parameter for each worksheet.
  - *Recoverable CO_2.* The recoverable CO_2 value is the number of grams of CO_2 recovered per gram of product for processes that release CO_2 that can be returned to the culture (e.g., flue gases from biogas combustion).
  - *Mass to recovery.* This is the mass sent to recovery per gram of product on a dry-gram basis.

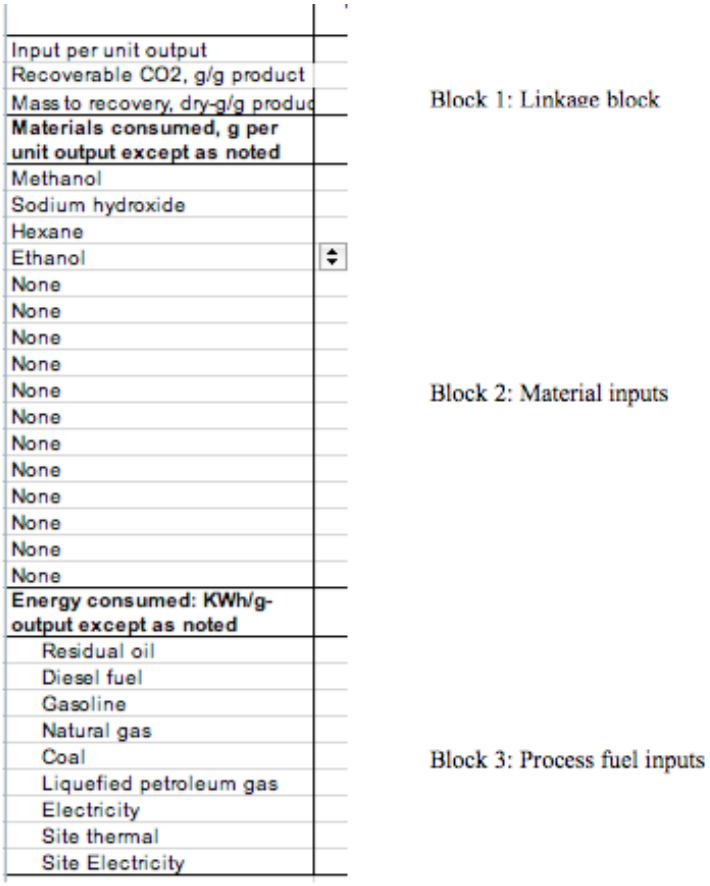

FIGURE 5 Three Blocks of the Process Description (The linkage block relates the process to other processes in the pathway. The other two blocks enumerate materials and fuels consumed by the process.)

TABLE 1 Definition of "Input per Unit Output" Parameter for Each Worksheet

Worksheet Name	Meaning of Input per Output Value
CO_2	Not used
Growth and 1st Dewater	Grams of CO_2 per gross dry-gram of algae grown
Remaining Dewatering	Dry-gram of algae required to produce one dry-gram of dewatered algae
Extraction	Dry-gram of dewatered algae required to produce one gram of extracted lipids
Recovery	Not used; material and fuel consumption are per dry-gram of material sent to Recovery

- Block 2 (materials input block) contains material inputs on a mass basis, unless noted otherwise. The material names are selected via drop-down lists configured from the materials table found on the "Materials" worksheet.

- Block 3 (process fuels input block) contains fuel inputs on an energy basis. These inputs, such as natural gas (NG), are provided by the model on an energy basis expressed in kilowatt-hours per gram (kWh/g) of product.

2.3.2 Process Description Example

DAF is a dewatering process that uses a coagulant to increase floc sizes and uses air bubbles to sweep flocs to the surface for separation. The process inputs are electricity and coagulant. If the process recovers 90% of the input algae, then 1.11 dry-grams of algae in suspension must be input per dry-gram of algae recovered by DAF, and the value of "input per unit output" is 1.11 dry-grams per dry-gram. If the unrecovered algae are discharged to recovery for AD, the "mass to recovery" value is 0.11. If chitosan is used for coagulation at 100 mg/L and the input solids are 1% by mass, then 0.01 g of chitosan is required per dry-gram of recovered algae, and 0.01 gram would be entered in Block 2 for material inputs. The process electricity would be input in Block 3. All other values in the process description are computed from these values.

2.3.3 Energy Unit, "Site-Electricity" Consumption, and "Site-Thermal" Consumption

APD consistently uses one energy unit in the process descriptions to facilitate computations: kilowatt-hours. This is true for all kinds of energy, including thermal.

Some algae fuel pathways include electrical power generation from the process residuals (e.g., biogas from AD of algae residuals). This power can be used on site to reduce the consumption of electricity from the power grid. Some process steps, however, would be unlikely to use site-generated power. For example, blowers that transport flue gas to the algae farm would use power from the grid, as would regional processing centers.

APD and GREET collaborate to compute the amount of power that could be exported, by subtracting the power that is used on site from the total power that is generated on site. To achieve this collaboration, processes in APD divide their electrical power consumption into "electricity" and "site-electricity" categories.

Some processes that require heat can satisfy their demand with heat produced by a combined heat and power (CHP) system. Processes divide their heat consumption into "site-thermal" and various process fuel categories. The "site-thermal" portion is met with heat from the CHP system, if possible. The value in the process description must be the net heat. If the process must use a fuel (e.g., NG), the gross fuel consumption is specified in the process description. If the CHP system does not provide sufficient heat, GREET will add additional process fuels to meet the balance, as described in Section 4.3.1.

2.3.4 Color Coding in APD Worksheets

Cells in the APD Excel file are color-coded to guide the user (Table 2). Usually, only yellow or green cells should be changed. Changing other cells might modify formulae and affect results elsewhere in the system.

TABLE 2 Colors Used in APD Cells

GREET interface	Blocks read by GREET are in tan cells.
Model inputs	Parameters for process computations are in yellow cells.
Tool inputs	Green cells are tools that help you compute model inputs. They do not affect the model until copied to a yellow parameter cell.
Error	Red cells flag error conditions.

2.3.5 GREET-APD Interface

APD and GREET exchange data through Excel named blocks. The transfer is one way: from APD to GREET. To transfer data from APD to GREET, click the grey area in the "Copy APD Results to GREET" button that is located on the "Copy to GREET" worksheet. Clicking that button will update the calculations in APD, copy the data in the named blocks to GREET, set GREET to study algal oil processing (rather than the processing of other oils like soybean), and cause the "Algae" worksheet in GREET to become the active worksheet. Table 3 shows the names of the blocks defined in Excel that are used when data are transferred to GREET.

TABLE 3 Names and Contents of Excel Blocks Used in the APD-GREET Interface

Block Name	Content
APD_CO2_Transfer	Process description for introducing CO_2 into the algae culture
APD_Growth_Cooling	Process description for cooling the photobioreactor (PBR)
APD_Growth_Nutrient_Use	Process description for growth nutrient use
APD_Growth_Summary_of_Water	Process description for water movement, including media circulation, makeup water supply, and movement to 1st dewatering
APD_Summary_Growth_1st_Dewater	Sum of APD_Growth_Cooling, APD_Growth_Nutrient_Use, and APD_Growth_Summary_of_Water
APD_Summary_of_CO2	Process description for CO_2 transport, transfer, and capture
APD_Summary_of_Extraction	Process description for cell disruption and extraction of metabolites
APD_Summary_of_Remaining_Dewatering	Process description for dewatering beyond first-level dewatering
APD_Summary_of_Recovery	Process description for recovery, including AD, electricity generation, and other co-products
APD_Materials	Materials that are included in the drop-down boxes

3 APD PROCESS INVENTORY

This section catalogs the processes in APD, describes any associated computations and models, and provides provenance for the data. The section is organized according to the worksheet in APD.

3.1 "CO_2" WORKSHEET

The "CO_2" worksheet computes the energy and materials associated with supplying the CO_2 required to grow algae. The amounts of energy required to concentrate CO_2 from flue gas, transport it to the site, and transfer it into the culture are combined to define the energy requirement for importing CO_2 to the site. GREET determines the total CO_2 demand of the pathway and determines the total CO_2 recovered in the recovery operation, then uses these results to compute the amount of CO_2 imported. The energy required to import CO_2 to the site is applied to the imported CO_2 portion, but only the energy required to transfer the CO_2 into the culture is applied to the recovered CO_2 portion.

3.1.1 Energy for Low-Pressure Pipeline Transport

This process computes the energy required to transport flue gas at low pressure. The calculation computes the power needed to compress a gas beyond atmospheric pressure (delivery pressure) by a specified amount (fan pressure), by considering the compressibility of the gas and the combined motor and fan efficiency. Default values are 5.8 kPa for the fan pressure and 50% for the combined motor and fan efficiency. Compressibility is computed from the ratio of the specific heat values, which is 1.395. Further details can be found in Frank et al. (2011).

3.1.2 Energy for Transfer to Pond

Transfer energy is computed on the basis of the transfer pressure and the combined compressor and motor efficiency. The computation is for a compressible gas as described by the ratio of specific heat values for the flue gas. The default parameters are a water depth of 1.5 m, efficiency of 67%, and flue gas density of 1.3 kg/m^3.

3.1.3 CO_2 Capture

The CO_2 capture block computes the energy consumption associated with concentrating the CO_2 from flue gas via the capture and regeneration of an absorber. Compression is not included. In APD, CO_2 is captured chemically (e.g., on an amine) and then released in a regeneration step that requires heat. The heat is taken from the steam system of the power plant; thus, the electrical yield of the plant is reduced. A so-called "conversion factor" is defined to be the ratio of the electrical energy lost per unit of energy taken for desorption. Values for this

conversion factor range from 15% to 25% in the literature, with smaller values predicted for future, improved systems. Together, the thermal energy for desorption and the conversion factor determine the equivalent lost electricity for capturing and releasing CO_2 (in kWh/kg CO_2).

The equivalent lost electricity for CO_2 capture and release is configured in APD by specifying the thermal energy for desorption and the conversion factor. Several sources were reviewed (Table 4). The default values in APD are 3.35 GJ/metric-ton CO_2 for desorption energy and 25% for the conversion factor.

The type of power plant and whether the CO_2 is captured from a portion of the power plant emissions or all of the plant emissions must be carefully considered when scenarios that involve CO_2 capture are being evaluated. GREET must be reconfigured accordingly. This work is in progress and is not supported at this time. Simply selecting CO_2 capture in APD will not give correct results. We have included the calculations here to facilitate collaborations with other researchers to develop the simulation in the future.

3.1.4 Condensation to Supercritical CO_2

A process for condensing flue gas from an oxyfuel electrical power plant was modeled in Aspen+. The model included initial three-stage compression and drying, CO_2 cleanup, argon purging, and an ammonia (NH_3) refrigeration block. Jointly, these achieved condensed CO_2 that meets pipeline specifications. Oxyfuel plants burn their fuel in a low-nitrogen, high-oxygen atmosphere to produce flue gas that is high in CO_2. This "pre-combustion approach" to CO_2 capture avoids post-combustion CO_2 absorption. The process conditions for CO_2 desorbed from an amine absorber and for CO_2 emitted from an oxyfuel combustion environment are similar enough that the oxyfuel model is a good approximation for the energy costs for condensation in both cases. The oxyfuel model studied several cases with varying concentrations (90% to 99%) of O_2. The condensation energy costs per mass of CO_2 were averaged over these cases, resulting in 1.8×10^{-4} kWh/g-CO_2.

3.1.5 Supercritical CO_2 Pipeline Transport

The energy for pipeline transport of supercritical CO_2, 159 Btu/ton/mile, was taken from GREET version 1_8d and converted to the APD unit of 4.24×10^{-8} kWh/g-CO_2/mi. A value for the transport distance must be entered (default is 50 mi).

3.1.6 Combining CO_2 Options

The various options just described may be combined to achieve a desired scenario. The energy costs for transfer to the pond or reactor are always included, although the corresponding pressure may be set to zero. To use low-pressure transport of flue gas, select just that option and leave all others set to "None." To use low-pressure transport of purified CO_2, select both low-

TABLE 4 Data Inventory for CO_2 Capture Energy[a]

			CO_2 Desorption from Solvent			Electrical Consumption (kWh/kg CO_2)			Overall	
Scenario	Pub. Date	Solvent	Thermal Energy (GJ/t CO_2)	Equivalent Lost Electricity (kWh/kg CO_2)	Conversion Factor	CO_2 Compression	Other	Total	Lost Electricity Production (kWh/kg CO_2)	Total Aggregate Energy (GJ/t CO_2)
Allstom (Nsakala et al. 2001)	2001	MEA		0.350				0.109	0.458	
Allstom	2001	MEA/DEA		0.092				0.171	0.263	
Feron 1995 (Feron 2006)	2006	NA	4.2	0.292	0.250	0.114	0.040	0.154	0.446	4.754
Feron 2005	2006	NA	3.2	0.178	0.200	0.108	0.020	0.128	0.306	3.661
Feron 2015	2006	NA	2.0	0.083	0.150	0.103	0.010	0.113	0.196	2.407
Fluor (Reddy et al. 2003)	2003	MEA								3.256
MHI KS-1 (Kamijo et al. 2004)	2004	KS-1	3.0			0.100	0.018	0.118		3.425
MHI KS-1 Improved (Okuzumi et al. 2010)	2010	KS-1								2.931
NETL 30% (Ramezan et al. 2007)	2007	Adv Amine	3.6	0.194				0.156	0.355	
NETL 50%	2007	Adv Amine	3.6	0.204				0.155	0.361	
NETL 70%	2007	Adv Amine	3.6	0.210				0.156	0.366	
NETL 90%	2007	Adv Amine	3.6	0.214				0.156	0.370	
Rao and Rubin (2002)	2002	MEA							0.462	
Rao et al. (2006)	2006	MEA	4.4							
Rao et al. (2006) 70%	2006	MEA	4.3	0.167	0.140			0.161	0.328	4.870
Rao et al. (2006) 90%	2006	MEA	4.4	0.171	0.140			0.152	0.323	4.947
Rao et al. (2006) 95%	2006	MEA	4.5	0.174	0.140			0.150	0.324	5.010

[a] Adv = advanced, DEA = diethanolamine, MEA = monoethanolamine, NA = not available, NETL= National Energy Technology Laboratory. Thermal energy and total aggregate energy are per metric tons (t). Feron 1995, 2005, and 2015 refer to scenarios reported in (Feron 2006).

pressure transport of flue gas and CO_2 capture; then set the mass fraction of CO_2 in the flue gas appropriately. To use supercritical CO_2 transport, do not include low-pressure gas pipeline transport. Instead, enable CO_2 capture, condensation to supercritical CO_2, and supercritical pipeline transport, and set related parameters. In this scenario, consider whether the pressure should be set to zero for transfer to culture in order to eliminate those energy costs.

The type of power plant and whether the CO_2 is captured from a portion of the power plant emissions or all of the plant emissions must be carefully considered when scenarios that involve CO_2 capture are being evaluated. GREET must be reconfigured accordingly. This work is in progress and is not supported at this time. Simply selecting CO_2 capture in APD will not give correct results. We have included the calculations here to facilitate collaborations with other researchers to develop the simulation in the future.

3.2 "NUTRIENTS" WORKSHEET

The "Nutrients" worksheet contains several tools that help set parameter values on other worksheets. These values are not used directly by APD. You must copy them or reference them, as needed, on the other sheets.

3.2.1 Algae Biomass Model

The biomass is described by the carbon fraction and carbon : nitrogen : phosphorus (C : N : P) molar ratios. A reference table is provided for the C : N : P content of protein, carbohydrates, and lipids from Lardon et al. (2009).

3.2.2 Heating Value Model

The whole algae lower heating value (LHV) is used to compute the renewable energy in the algae process. If a scenario considers lipid-extracted algae (LEA) as a co-product on an energy basis, the LHV of the LEA is used to compute the energy allocation. (This scenario is not typical, however.)

The "Nutrients" worksheet includes tools to estimate heating values for algal biomass when measured values are not available. The biomass is described via protein, carbohydrate, and lipid fractions. LHVs per macromolecule from Lardon et al. (2009) are used to compute the LHV of the whole biomass and the lipid-extracted biomass (Table 5). The latter is computed by approximating that all lipids are removed. If the protein, carbohydrate, and lipid fractions are f_P, f_C, and f_L and the corresponding LHVs are C_P, C_C, and C_L, the LHV for the lipid-extracted biomass is estimated as $(f_P * C_P + f_C C_C) / (f_P + f_C)$.

TABLE 5 Lower Heating Values for Macromolecules from Lardon et al. 2009

Fraction	LHV (MJ/kg)	LHV (Btu/ton)
Protein	15.5	13,356,312
Carbohydrate	13	11,202,068
Lipid	38.3	33,003,016

Table 6 shows the variability of the LHVs for different algal macromolecular compositions as reported for several *Chlorella* in Sialve et al. (2009).

TABLE 6 Variability of Lower Heating Value for Different Algae Macromolecule Compositions

Protein (weight percent [wt%])	29.0	7.0	32.0	28.0	38.0	36.0
Carbohydrate (wt%)	51.0	55.0	41.0	11.0	52.0	41.0
Lipid (wt%)	18.0	40.0	29.0	63.0	11.0	23.0
Whole biomass LHV (Btu/ton)	15,526,928	20,297,286	18,437,742	25,763,895	14,530,806	16,991,814
Lipid-extracted biomass LHV (Btu/ton)	11,982,981	11,445,289	12,146,394	12,748,705	12,111,638	12,209,247

The default values in GREET are obtained by averaging, but correct values should be set by the analyst for the species being studied. The average LHV for whole algae and LEA are 18,591,412 Btu/ton and 12,107,367 Btu/ton, respectively.

3.2.3 Biogas Model

The data from Sialve et al. (2009) and the macromolecular composition from the heating value model are used to compute the theoretical maximum methane (CH_4) yield per gram of volatile solids for protein, carbohydrate, and lipid. The computation assumes 100% digestibility. The methane fraction is then used to compute the CO_2 yield. These values may be used in the "Recovery" worksheet after adjusting for digestibility. See the discussion in Frank et al. (2011) regarding studies of algae AD and empirical estimations of yields.

3.2.4 Nutrient Mass Balance Model

The nutrient mass balance model considers the flows of N and P in the system. Several parameters must be provided in the green cells in the flowchart. The cells in the flowchart, and their parameters, are as follows:

- *New nutrients.* This describes the extra nutrients that must be added to balance the mass flows. It is the difference between the nutrient content of the algae and the return flows of N and P minus losses to volatilization losses for N.

- *Algae process, through extraction.* This describes the total N and P in 1 gram of algae biomass. Values are set from the C : N : P ratios in the algae biomass model above.

  – Parameters are the percentages of N and P lost to product. These describe the flow of nutrients to the product (e.g., phospholipids in the extracted lipids).

- *Lipid extracted algae.* This shows the N and P content of the LEA.

- *Retained extract.* This shows the N and P contents of the metabolites extracted from the algae. This N and P are treated as lost.

- *AD solid residue.* This describes the solids portion of the AD residue. The "Share of LEA" for N and the share for P describe the fractions of N and P in the LEA that end in the digester solids. The balances go to the AD liquid residue. The utilization percentages describe how much of the N and how much of the P in the sludge are utilized (bioavailability in the soil amendment co-product) or account for inefficiencies. For example, for soil amendment co-products made from the sludge, the utilization percentages could reflect imperfect mineralization of N. The shares of N and P lost and displaced are then computed.

- *AD liquid residue.* This is the liquid portion of the AD residue. The disposition of the liquid is among (1) the share returned to the algae, (2) the share used for soil amendment, and (3) the share sent to treatment and discharge.

- *Extra AD nutrients.* This describes additional N and P required by the digester, expressed per gram of harvested, dewatered algae.

- *Displaced algae nutrient.* This describes the share of the residue liquid fraction that is returned to the culture. The block accounts for utilization efficiency (e.g., volatilization during return). Inefficiency is treated as lost N and P. The phosphorus portion is used in the catalytic hydrothermal gasification computations on the "Recovery" worksheet.

  – Parameters: Utilization efficiencies of N and P; 100% means complete utilization.

- *Soil Amendment.* This describes the share of the residue liquid fraction that is used to displace fertilizer. The block can be used to account for volatilization of ammonia.

  - Parameters: Utilization efficiencies of N and P. 100% means complete utilization.

- *Treatment and discharge.* This accounts for loss of N and P in any AD waste.

A summary section confirms the N and P mass balances in the flowchart. The mass of nutrients displaced by the digestate solids is also computed by determining the ratio of the mass of the nutrients in the digestate to the dry mass of the digestate. The values for N and for P as P_2O_5 are in the tan cells and are automatically copied to GREET via the "Copy to GREET" button. The total weight fractions of C and N are also computed (without regard to bioavailability) and are also copied to GREET.

3.2.5 Media Composition

The media composition table lists several compounds commonly used to prepare culture media. The media are described in grams per liter of these nutrients. The table is summed, and the total N and P concentration (mol/L) is computed by assuming the algae concentration at harvest input on the "Growth and 1st Dewater" worksheet. That parameter must be set correctly. These concentrations may be compared with the values in the mass balance model in the "New Nutrients" box. When they match, the g/L of each nutrient in the table may be entered in the materials block in the "Growth and 1st Dewater" worksheet. Note that the actual concentrations in the media will be higher if nutrients are being recycled. The computation here is just for the share of new nutrients being added.

3.3 "GROWTH AND 1ST DEWATER" WORKSHEET

The "Growth and 1st Dewater" worksheet accounts for almost all water movement in the process; water for growth and water for first-level dewatering are treated together for that reason. This worksheet describes the energy and nutrient requirements for these operations. Two scenarios are modeled: open pond and photobioreactor (PBR). Use the drop-down box in the Growth Method Specification section to choose the growth method, then set the relevant parameters for the selection as described below.

Facility Parameters

- Algal oil fraction: Weight-based fraction of dry mass from lipids
- Productive days per year: Number of growing days per year

Pond/Reactor Common Parameters

- Energy to pump water
- Energy to pump culture: Used to compute on-site movement of culture to first-level dewatering
- CO_2 total supply rate: Total amount of CO_2 delivered to the pond per gram of produced algae, before losses (The CO_2 total supply rate is combined with the CO_2 loss parameter (below) to determine total CO_2 demand per gram of biomass.)

Pond Parameters

- Specific productivity: Area productivity in dry grams per square meter per day
- Circulation power for pond: Circulation power for a paddle wheel (This was analyzed in several sources. Frank et al. (2011) describes how the default value, 48 kWh/ha/d, was determined for a mixing velocity of 25 cm/s.)
- Evaporative loss from pond: The default value, 0.229 L/g, was computed from an average pan evaporation of 0.157 in. per month (typical of Texas) and a lake/pan correction factor of 0.75.
- CO_2 loss: Fraction of the CO_2 total supply rate that is not captured in algal biomass
- Media loss overhead: Volume of water lost per dry-gram of algae for reasons other than evaporation (e.g., leaching, blowdown from salt accumulation, discarding media after pond contamination) (It is assumed that all nutrients and biomass in the culture at the time are lost with the water.)
- Output concentration: Algae concentration of the culture at harvest (dry-g/L).

Reactor Parameters

- Specific productivity: Volumetric productivity in g-algae/L-culture/d
- CO_2 loss, as fraction: See the pond parameter description
- Media loss overhead: See the pond parameter description
- Evaporative loss: Useful for PBRs that are cooled by partial immersion in a bath. There is no cooling-water circulation power, but there are evaporative losses. Evaporative loss is specified (L/g-algae). APD adds the required water to the fresh-water demand and to the energy for supplying fresh water.
- "Evaporative cooling demand": Volume of water required for cooling, expressed in L/L of culture volume/d (i.e. it is the volume evaporated)
- "Circulation energy for spray evaporative cooling": Energy required to circulate 1 L of water in the spray system, expressed in kWh/L-cooling water.
- "Spray evaporative cooling water loss rate": Percentage of circulated water that evaporates, expressed as a unitless percentage (i.e., ratio of the volume evaporated to the volume circulated)
- Output concentration: See the pond parameter description.

The evaporative cooling demand, the spray evaporative cooling water loss rate, and the specific productivity are combined to compute the volume of spray-cooling water that is circulated per gram of algae. The energy required for spray-cooling is computed by multiplying the circulation energy for spray-cooling by the volume of spray-cooling water that is circulated. This energy is added to the site electricity demand. The volume of spray-cooling water circulated is multiplied by the loss rate to determine the water use for spray cooling. This is included in the fresh-water demand and energy for moving water on site and affects the site electricity demand.

First-Level Dewatering Parameters

- Output algae concentration from first dewatering: Concentration entering further dewatering

3.4 "REMAINING DEWATERING" WORKSHEET

3.4.1 Dissolved Air Flotation

DAF was described in several sources (Harris et al. 1982; Sim et al. 1988; Uduman 2010). Harris describes the Computer-Assisted Procedure for Design and Evaluation of Wastewater Treatment Systems (CAPDET), a detailed process design and cost estimating system for wastewater treatment systems. Harris et al. and Sim et al. report similar energy numbers for DAF: 1.33×10^{-4} kWh/dry-g (Harris et al.) and 1.48×10^{-4} kWh/dry-g (Sim et al.). Uduman's value is substantially higher: 1.67×10^{-3} kWh/dry-g. The default value in APD is the one from CAPDET. CAPDET computes the power consumption from the dry weight of the recovered solids. The value, 1.33×10^{-4} kWh/dry-g, corresponds to processing the algae produced by 2,000 ha having a productivity value of 25 g/m^2/d. The result depends on the biomass rate only weakly; it increases by 4% if the throughput is halved and decreases by 4% if the throughput is doubled.

DAF generally uses a coagulant. The default model assumes chitosan is used at 0.01 g/dry-g algae and that the algae recovery efficiency is 90% (Uduman 2010).

3.4.2 Thermal Drying

The thermal drying model multiplies the latent heat of vaporization for water by a vaporization inefficiency coefficient to obtain the heat for drying. APD computes the mass of water corresponding to the change in moisture level and computes the energy needed to raise the water temperature to 100°C and the energy of vaporization (scaled by the efficiency coefficient).

Thermal Drying Model Parameters:

- Ratio of thermal energy use to latent heat of evaporated water: Default value of 1.5. (Amos 1998; Mohn 1980).
- Ambient temperature: Average ambient temperature, expressed in °C.
- Initial solids: Entering solids, expressed in wt%
- Final solids: Exiting solids, expressed in wt%

3.4.3 Belt Filter Press

The U.S. Environmental Protection Agency (EPA) manual *Energy Conservation in Municipal Wastewater Treatment* (Wesner et al. 1978; Wang et al. 2007) plots the electrical energy required (in kWh/yr) for the operation of BFPs. The parameterization is for BFP volume (in cubic feet) for three different levels of influent total solids (4%, 6%, and 8%). It is customary to use the mass or volume of the solids to be de-watered in one single cycle as the sizing parameter for BFPs. The largest volume in the plot is 1,000 ft^3. Because large processes are anticipated, this point is used as the reference (see Table 7). APD includes the three cases as separate unit processes in order to guide the user with regard to input conditions and associated

energy requirements, although the user may enter any energy requirements he or she desires. If coagulants are needed, they should be included in the materials consumption section.

Belt Filter Press Parameters for Each (4%, 6%, 8%) Total Solids Input rating:

- Energy: Expressed in kilowatt-hours per kilogram of influent
- Recovery efficiency: Recovered solids, expressed as a percentage

TABLE 7 Belt Filter Press Characteristics from Wesner et al. 1978

Parameter	Value
Input total suspended solids (TSS) (%)	0.5–10
Output TSS (%)	12–50
Filter press volume (ft^3)	1,000
Filter press volume (L)	28,317
Cycle length (h)	2
Solid density, assumed to be the same as water density (kg/L)	1
Mass of solids in filter press (kg)	28,317
Electrical energy, 4% total solids (kWh/yr)	900,000
Electrical energy, 6% total solids (kWh/yr)	500,000
Electrical energy, 8% total solids (kWh/yr)	400,000
Electrical energy, 4% total solids (kWh/kg-influent)	7.26×10^{-3}
Electrical energy, 6% total solids (kWh/kg-influent)	4.03×10^{-3}
Electrical energy, 8% total solids (kWh/kg-influent)	3.23×10^{-3}

3.4.4 Dewatering Centrifuges

Both the energy consumption of centrifuges and their potential output solids concentrations vary considerably, depending on the type of centrifuge. Two types characterized for algal biomass dewatering are shown Tables 8 and 9. Mass retention efficiencies of 85–97% are reported for self-cleaning disc stack centrifuges and 85–95% are reported for decanter bowls (EPA 1979). Harris et al. (1982) reports a "rule of thumb" of 1 horsepower/gallon per minute (HP/GPM) (i.e., 3.298×10^{-3} kWh/g-suspended matter). Since this value falls between that of the disc stack centrifuge and decanter bowl, APD uses values of 3.3×10^{-3} kWh/g-algae for electrical power and 95% for retention efficiency .

Centrifuge Parameters:

- Initial solids: solids % entering the unit.
- For each of disc-stack and decanter bowl:
  - Energy: Expressed in kilowatt-hours per kilogram of influent
  - Recovery efficiency: Recovered solids, expressed as a weight percentage

TABLE 8 Self-Cleaning Disc Stack Centrifuge Characteristics (Mohn 1980; Grima et al. 2007)

Parameter	Value
Input TSS (%)	0.1–1
Output TSS (%)	5–12
Electrical power per volume flow (kWh/m^3)	1
Liquid density (kg/L)	1
Calculated electrical power per mass flow (kWh/kg)	1.0×10^{-3}

TABLE 9 Decanter Bowl Centrifuge Characteristics (Mohn 19080; Grima et al. 2007)

Parameter	Value
Input TSS (%)	0.5–4
Output TSS (%)	10–22
Electrical power per volume flow (kWh/m^3)	8
Liquid density (kg/L)	1
Calculated electrical power per mass flow (kWh/kg)	8.0×10^{-3}

3.4.5 Fournier Rotary Press

Fournier Industries (Quebec, Canada) manufactures a device for dewatering sludge after the addition of a coagulant. The device can be deployed in single-channel or multiple-channel configurations. In multiple-channel configurations, several instances of the basic device are driven from a shared motor shaft. A review of the manufacturer's data indicated that "ganging" multiple channels improved the energy efficiency when up to three channels were used. Beyond that point, scale-up appeared to be by replication, and no further energy efficiency gains occurred. The energy consumption in APD corresponds to the three-channel case.

Fournier Rotary Press Parameters:

- Energy: Expressed in kilowatt-hours per kilogram of influent solids
- Recovery efficiency: Recovered solids, expressed as a percentage

3.5 "EXTRACTION" WORKSHEET

The "Extraction" worksheet accounts for the disruption of the algal cell plus the extraction of the product.

3.5.1 Pressure Homogenization

Pressure homogenization is an established process used to disrupt bacteria in waste-activated sludge. GEA Niro Soavi manufactures homogenizers ranging from 100 to 1,500 bar and up to 5,000 L/h and has reported some experiments with algae. It observed 79% homogenization of *Chlorella* per pass at 600 bar and 2,000 L/h. At 10 wt% solids, this is 365 kWh/dry ton for two passes. The process modeled in Stephenson et al. (2010) assumes 22 wt% from the decanter centrifuge (i.e., 168 kWh/dry ton for homogenization); however, discussions with GEA Niro Soavi indicate that it is unusual to work above 20% solids because of pumping difficulties and homogenizing efficiency. In EPA (2006), pressure homogenization energy consumption was 750 kWh/dry ton for 4–7-wt% solids, and it was 200 kWh/dry ton with 90% disruption efficiency in Davis (2010) . The default values used by APD are 183 kWh per dry metric ton and 90% efficiency, corresponding to 20 wt% input and some reduction in efficiency for the higher solids content.

3.5.2 Hexane Extraction

Hexane extraction of lipids from wet biomass is an experimental process that has been studied only at the bench scale The process is summarized in APD by several parameters. Frank et al. (2011) describes how the default values were determined.:

Hexane Extraction Parameters:

- Location: Describes whether the extraction is performed on site or at a remote site; if it is performed at a remote site, transportation needs are computed
- Hexane consumption: Mass of hexane consumed (lost) per gram of oil produced
- Net heat required: Net heat energy required by the process
- Heat source: Heat obtained either from the CHP system on site or from NG (Select either “CHP” or “NG” in the drop-down menu)
- Boiler efficiency: Boiler efficiency when NG is used to provide steam
- Electricity required: Electrical energy required per gram of oil extracted

3.6 “CONVERSION” WORKSHEET

Conversion by transesterification, renewable diesel, and renewable gasoline is modeled in GREET (Huo et al. 2008). The “Conversion” worksheet is a placeholder for future expansion.

3.7 “RECOVERY” WORKSHEET

The “Recovery” worksheet describes recovery per gram of material sent to the recovery process. This is a mixture of algae lost upstream plus lipid-extracted algae. There are two recovery processes presently, described below. The recovery worksheet computes the amount of methane and CO_2 recovered and returns those values to GREET. GREET models electricity

generation, methane export as co-product, and residual export as co-product. GREET also computes the CO_2 produced and allows it to be recovered for re-use during algae growth.

3.7.1 Anaerobic Digestion

Biogas yield is specified on a dry basis (cubic meters per kilogram of dry biomass) to compute the produced biogas volume. The yield must account for digestibility. The biogas is treated as a mixture of methane and CO_2; hence, the second parameter is the methane fraction on a volume basis. The mass of methane and metabolic CO_2 (i.e., from digestion rather than combustion of methane) are computed and returned to GREET for co-product analysis. Frank et al. (2011) describes the default values and how they were determined.

AD Parameters:

- Volatile fraction: Mass fraction of volatile solids in total solids
- Methane yield: Volumetric yield (liters) per mass (grams) of volatile solids at standard temperature and pressure
- Biogas CH_4 fraction: On a volume basis, the fraction of methane in the biogas
- Carbon: Expressed as wt% of AD feed.
- Heat required: Amount required per mass (g) of digested residue
- Electricity required: Amount required per mass (g) of digested residue

3.7.2 Genifuel Gasification Process

The Genifuel process is included as an alternative to AD. This process is based on a catalytic process developed at Pacific Northwest National Laboratory (Elliott and Sealock 1996). Frank et al. (2011) describes the parameters and how the default values were determined.

4 GREET EXPANSION FOR ALGAL FUELS

Several documents on the GREET web page (http://greet.es.anl.gov/publications) describe the portions of GREET that are shared by the algae fuel pathway and other pathways (e.g., Wang 1999a,b, 2001).

4.1 FUEL PRODUCTION (CONVERSION) FROM ALGAL LIPIDS

The current version of GREET models several fuel production processes:

- Transesterification of algal oil to biodiesel;
- Renewable Diesel I (SuperCetane), by hydrotreating algal oil;
- Renewable Diesel II, by UOP hydrodeoxygenation of algal oil; and
- Renewable gasoline.

Details are presented in Huo et al. (2008).

4.2 CO-PRODUCT TREATMENT

Processes consume energy and produce multiple products and emissions. For example, corn ethanol produces feed supplements along with the ethanol fuel; therefore, not all the energy inputs and process emissions should be charged to the fuel product, There are two general approaches to this computation: allocation method and displacement method. The allocation method is appropriate for LCAs when the primary product and co-products can be measured on the basis of a single factor (such as mass or energy content).

4.2.1 Allocation Method

The allocation method allocates feedstock[1] use, energy use, and emissions between the primary product and co-products on the basis of the mass, energy content, or market value of the products. For example, in an energy-based allocation, if E_i is the energy content of the i^{th} product and E_T is the total energy content of all products combined, then E_i/E_T of the process energy and emissions are assigned to the I^{th} co-pro duct, and the main product is credited by that amount. In a mass-value-based allocation method, the masses of the primary product and co-products are used to split the burden of energy input, feedstock input, and pollutant emissions. In an energy-value-based allocation method, the energy content of the primary product and co-products is used to split the burden of energy input, feedstock input, and pollutant emissions. In a market-value-based allocation method, the market value of the products becomes the determining factor

[1] "Feedstock" in this context refers to material inputs to the process. For example, algal oil is the feedstock for transesterification to biodiesel, and dewatered algal biomass is the feedstock for algal oil production.

in splitting the burden. The market-value-based allocation method is subject to variations in the product prices, which may lead to significant uncertainties in the LCA results.

4.2.2 Displacement Method

In the displacement method, a conventional product is assumed to be displaced by a co-product of the process under evaluation. The life-cycle energy that would have been used and the emissions that would have been generated during production of the displaced product are counted as credits for the primary product. These credits are subtracted from the total energy use and emissions burden of the process under evaluation. In market-value allocation, the inputs and emissions of the process being analyzed are divided by the market values of the co-products. In the displacement method, it is the emissions of the displaced processes that are considered. Thus, the displacement method involves expanding the system boundary to include the displaced products.

The difficulty with the displacement method is identifying the displaced products and their life-cycle energy use and emissions. Also, if the amounts of the co-products are relatively large when compared with the amount of the primary product for a given process, the displacement approach becomes inappropriate for estimating the energy and emissions burden of the primary product because the co-product volumes may exceed the market size. The displaced emissions are then overestimated.

4.3 CO-PRODUCTS FOR ALGAL-OIL-BASED PATHWAYS

Five co-products from the production of algal oil are considered: electricity; heat; bio-methane; nitrogen and phosphorus fertilizers made from AD residues (digestate solids); and LEA as animal feed (Figure 6). Electricity and heat can be produced directly from the combustion of LEA or from the combustion of biogas produced by digestion or catalytic hydrothermal gasification of the LEA. Figure 6 shows the possible flows.

APD computes the total LEA per gram of extracted lipid and the amount of methane and CO_2 formed during biogas production (AD or catalytic gasification) per gram of LEA. GREET is configured by the user to choose how the LEA is split among the three co-product flows: biogas production, direct combustion, and animal feed. These fractions are f_1, f_2, and f_3 in Figure 6. The biogas is divided into a portion for combustion in the CHP system to produce electricity and heat and a portion for being upgraded to pipeline-quality bio-methane.

4.3.1 Electricity and Heat

Electricity and heat can be produced from the combustion of algae biomass or biogas produced from AD or catalytic gasification. If the biomass residue is combusted, the moisture

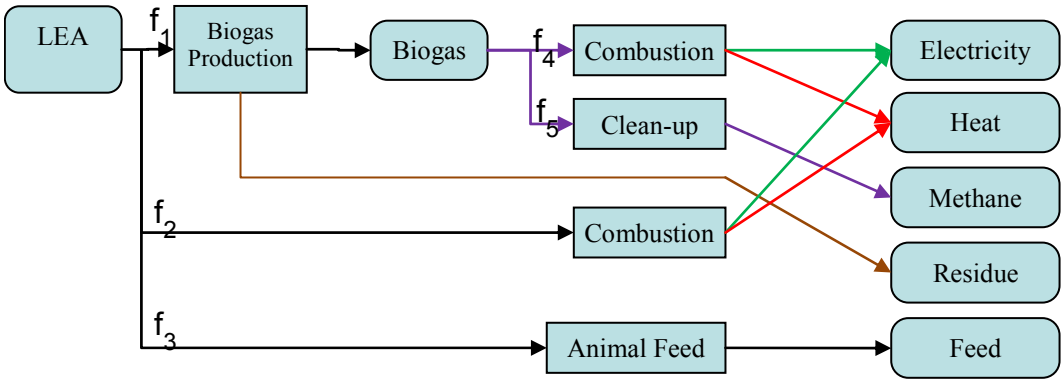

FIGURE 6 Co-Products for Algal-Oil-Based Pathways (Biogas production is either AD or catalytic hydrothermal gasification.)

content must be specified. Electricity can be consumed on site for process needs, or it can be exported. In the displacement method, the exported electricity can displace electricity from a selected generation mix, a natural gas combined-cycle (NGCC) plant, a coal integrated-gasification combined-cycle (IGCC) plant, or a biomass IGCC plant. If the amount of electricity produced on site is smaller than that required for process needs, grid electricity is used to supplement the deficit.

Heat from combustion of biomass or biogas is available for reuse on site and for export. In the displacement method, the exported heat can displace the same amount of heat produced from an NG boiler whose efficiency is 80%. Similarly, if the produced heat is not sufficient to cover the heat required by the processes, the same NG boiler is assumed to provide the deficit.

Three CHP systems are included in GREET. The key parameters are the electrical efficiency and the heat recovery rate. The electrical efficiency is the energy of the electricity produced divided by the energy of the fuel consumed on an LHV basis. The heat recovery rate is the fraction of the heat in the exhaust after electricity generation that is recovered as useful heat by the CHP system. If F is the energy in the fuel, ε_E is the electrical efficiency, $Q_{exhaust} = F(1 - \varepsilon_E)$ is the heat in the exhaust, and Q_r is the recovered useful heat, then the heat recovery rate is $Q_r/Q_{exhaust}$. This is not the same thing as the total CHP efficiency, Q_r/F. The heat recovery rate is specified on an LHV basis. The default CHP parameter values are described in Frank et al. (2011).

4.3.2 Bio-Methane

Since exported biogas should be improved to pipeline-quality bio-methane, the energy and emissions associated with the cleanup process should be taken into account, as should the credit for displaced NG. Since the quality of biogas from AD is similar to that of landfill gas (as compared with conventional well gas), the process assumptions for landfill gas cleanup are used. Then, if the displacement method is used, the energy and emissions associated with producing the same amount of North American NG are accounted for as a credit.

4.3.3 Anaerobic Digestion Residues

Nutrients can be recovered from AD residues and used for algae growth, or the residues can be used as an agricultural fertilizer. If the residues will be used on site, use the "Nutrients" worksheet in APD to compute the amount of each nutrient recovered, and then reduce the nutrient consumption values accordingly on the "Growth and 1st Dewater" worksheet. The values on the "Growth and 1st Dewater" worksheet must be set by hand.

When the AD digestate solids are exported as soil amendments, they displace conventional fertilizers at ratios defined by the user. Ratios are specified for the displacement of nitrogen and P_2O_5 on a mass basis. Carbon sequestration and nitrous oxide (N_2O) emissions are computed from the carbon and nitrogen portions of the residue. The "APD Nutrients" worksheet computes these values. The nitrogen utilization efficiency can be used to account for the bioavailability of nitrogen in the residue. The carbon-sequestration fraction specified in GREET is the carbon sequestration rate (grams of C sequestered per gram of C in the solids).

The displacement ratios for N and P_2O_5 and the weight percents of carbon and nitrogen in the residue are copied to GREET when the "Copy to GREET" button is clicked.

The transportation of the AD residue to soil is also included. The solids content (wt%) must be specified.

4.3.4 Animal Feed

Allocation methods use user-provided values for energy content and market value. Displacement methods use user-provided values for emissions. The user-provided values are per kilogram of feed. Energy and emissions are entered in the materials section at the bottom of the "Algae" worksheet. Market values are added at the right-hand side of the "Key Parameters for Dealing with Co-products" section.

4.3.5 Carbon Dioxide

The CO_2 from biomass/biogas combustion and AD can be returned to the culture used for the algae growth in addition to the CO_2 recovered from other processes. The recycled CO_2 reduces the amount of imported CO_2, thereby reducing the energy and emissions associated with CO_2 acquisition and delivery. CO_2 from off site is charged with both transport (to site) and transfer (into culture) energy costs. Recovered CO_2 is charged only with the energy cost for transferring CO_2 to the culture. The APD processes define the CO_2 demand and CO_2 recovery. GREET balances the two to compute the shares of CO_2 from on site versus off site.

4.3.6 Discarded Co-Products

Portions of each co-product can be discarded. If a co-product is discarded, no credit is given to the fuel process for that portion.

4.4 "ALGAE" WORKSHEET

The "Algae" worksheet in GREET consists of six major sections: (1) key input parameters for processes, (2) key input parameters for dealing with co-products, (3) shares of combustion processes for each stage, (4) calculations of energy consumption and emissions for each stage, (5) summary of energy consumption and emissions expressed as Btu or grams per million Btu (mmBTU) of fuel throughput at each stage, and (6) materials. On the basis of the parameters in the first three sections, the fourth section calculates the energy and emissions for each stage, with co-product credits taken into account, and the fifth section summarizes the energy and emissions associated with the produced fuel.

4.4.1 Key Input Parameters

4.4.1.1 Scenario Control

The Scenario Control drop-down menu can be set to one of three values: "Set with APD," "Low-A," or "Low-B." When "Copy to GREET" is clicked in APD, data are copied to GREET, and the Scenario Control section is set to "Set with APD" to use the copied data. If you use GREET without any modifications after downloading, "Set with APD" will already have values corresponding to the baseline scenario described in Frank et al. (2011). The "Low-A" and "Low-B" scenarios are also defined in Frank et al. You can switch between these scenarios by selecting one and then forcing GREET to update all computations.

4.4.1.2 Material Properties

See Section 3.2.2.

4.4.1.3 Natural Gas Boiler Efficiency for Heat

This is the efficiency for producing heat from NG when the CHP system does not satisfy the total site demand for thermal energy.

4.4.1.4 Transportation of Water

The distance for transporting water (fresh water and media make-up water) has been set to zero because our investigation of water delivery energy is not complete. The columns labeled "Media water" and "Fresh water" in the block labeled "Energy Consumption and Emissions from Material Production for Algae Pathways" at the bottom of the "Algae" worksheet page can be given values for water delivery by the investigator if desired. Those values will be included in the analysis. Values, if entered, should include all upstream energy consumption and emissions associated with delivering 1 kg of water to the site. Otherwise, if distances are changed from the default value of zero, incorrect energies will be computed.

4.4.1.5 Transportation of Algae Biomass to Extraction

GREET computes the energy and emissions when algae are transported to a regional extraction facility. The amount of biomass transported and the amount backhauled are computed in APD, while the transport distance and mode are set in GREET. The transportation distance (default is 50 mi), transportation mode (default is heavy heavy-duty truck), and solids content of the biomass (default is 80%) are set in this block.

4.4.1.6 CHP Configuration

This drop-down menu can be set to either "Turbine" or "ICE" (corresponding to gas turbine and internal combustion engine systems). The selection determines which data from the "Combined Heat and Power Parameters" table will be used. Those parameters are described in Section 4.3.1.

4.4.1.7 Anaerobic Digestion

The "Methane Loss from Biogas Production" parameter determines the amount of fugitive (leaked) methane emissions from the pathway. The value is the amount of methane lost, expressed as a percentage of the total methane produced.

4.4.1.8 AD Digestate Handling

Parameters are as follows:

- Solids content: Weight percent of solids when digestate is trucked off site for use.
- Transportation distance: Distance (in miles) that the digestate is trucked off site for use.

- Carbon sequestration by AD residue: How much of the carbon in the digestate is sequestered in the soil. This provides an emissions credit. The value is the ratio of the grams of carbon sequestered to the grams of carbon in the digestate.

- NO emissions from AD residue: Emission factor for NO, expressed as kg NO-N per kg-N applied, where kg-N applied is the total N in the residue. This parameter is set to zero pending further research.

- N_2O emissions from AD residue: Emission factor for N_2O given in kg N_2O-N per kg-N applied. The default value is 1.0 kg N_2O-N/kg-N (Frank et al. 2011).

4.4.2 Key Input Parameters for Dealing with Co-Products

For algae growth, dewatering, and extraction, four methods of handling co-products are available: (1) a displacement method, (2) an energy-based allocation method, (3) a market-value-based allocation method, and (4) a hybrid method. In the hybrid method, the displacement method is applied for AD residue and animal feed, while the rest of co-products are handled by the energy-based allocation method. For the conversion (or fuel production) step, displacement, energy-based allocation, market value-based allocation, and mass allocation methods are available. In addition to the co-product handling methods, a user can select the following options: the amounts of co-products to be exported or discarded; the shares of algae biomass for anaerobic digestion, for combustion, and for export as animal feed; the shares of biogas for combustion and for cleanup; the market values of co-products; and the displacement ratio of fertilizers by AD residue.

4.4.3 Transportation

Several transportation steps must be considered: the transportation of extracted lipids to the fuel production facility, transportation of the fuel from the production facility to a distribution terminal, and transportation of the fuel from the distribution terminal to a service station. The default values are described in Frank et al. (2011). They may be changed via the "T&D" worksheet in the columns labeled "Algae oil" with the sub-column "Oil Extraction to Biofuel Plant," where transportation mode shares are defined, and in the column "Algae oil" with the sub-columns, "Barge," "Pipeline," "Rail," and "Truck," where distances are set. The configurations for transportation to the station and to the terminal are identical to those for soybean-oil.

4.5 OTHER RELEVANT WORKSHEETS

Relevant parameters on other worksheets affect the algae LCA results. These are described here.

4.5.1 "Inputs" Worksheet

Many portions of the "BioOil" worksheet are shared by several oil-based fuels, including soybean, palm, rapeseed, jatropha, camelina, and algal oils. The parameter, "Feedstock for bio-oil based fuels" must be set to algae when studying algal biofuels. The "Copy to GREET" button in APD automatically sets this parameter correctly when clicked; otherwise, you should set it yourself when studying algal biofuels.

The electricity mix parameter on the "Algae" worksheet describes the displaced electricity, but the electricity mix consumed by the process is defined on the "Inputs" worksheet.

Because biodiesel, renewable diesel, and renewable gasoline are blended with conventional diesel and gasoline before use, LCA results for algal biofuels are weighted averages of the biofuel and conventional fuel pathways (biodiesel or renewable diesel mixed with conventional diesel, and renewable gasoline mixed with conventional gasoline). By default, the blend contains 20% biofuel. Other blends can be specified on the "Inputs" Worksheet.

4.5.2 "BioOil" Worksheet

Parameters on the "BioOil" worksheet affect calculations for transesterification of algal lipids (e.g., the parameters for co-products). See "Key Parameters for Dealing with Co-products of Vegetable Oil-Based Fuel" on the "BioOil" worksheet.

4.5.3 "Results" Worksheet

GREET reports the LCA results in the "Results" worksheet in three stages: feedstock, fuel, and vehicle operation. The feedstock stage for algal pathways includes all operations through oil extraction and transportation of the oil to the fuel production facility. The fuel stage includes all operations required to convert the algal oil to fuel and transport it to the filling station. The vehicle operation stage accounts for the direct fuel consumption and emissions based on fuel economy and emission factors.

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