Supporting Information

for

Growing Algae for Biodiesel on Direct Sunlight or Sugars: A Comparative Life Cycle Assessment

Nolan D. Orfield[*,1], Robert B. Levine[2], Gregory A. Keoleian[1,3], Shelie A. Miller[1,3], Phillip E. Savage[2]

[1] School of Natural Resources and Environment, University of Michigan, Ann Arbor
[2] Department of Chemical Engineering, University of Michigan, Ann Arbor
[3] Department of Environmental Engineering, University of Michigan, Ann Arbor
*nolando@umich.edu

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Carbon Accounting

As with all biofuels, the life cycle assessment of algal biodiesel requires close attention to both the biogenic carbon exchanges (i.e. removal during photosynthesis and natural emissions in reactors, anaerobic digesters, and farming emissions) and anthropogenic carbon emissions (i.e. from combusting natural gas for process heat or the emissions from the electrical grid and life cycle of other inputs). The waterfall plots shown in Figure S1 illustrate this carbon accounting. The contributions to the global warming potential (GWP) from sugarcane farming that are shown on the right portion comprise the fossil emissions (such as tractor fuel) while the biogenic portion of the sugarcane cultivation emissions, shown on the left portion of the plot, represents carbon fluxes from portions of the crop that were initially removed from the atmosphere by the biomass but do not end up in the fuel (such as soil carbon exchanges or bagasse combustion). The “Digester Outputs” category refers to avoided emissions from energy recovery, both thermal and electrical, by combustion of the biogas in a combined heat and power (CHP) system.

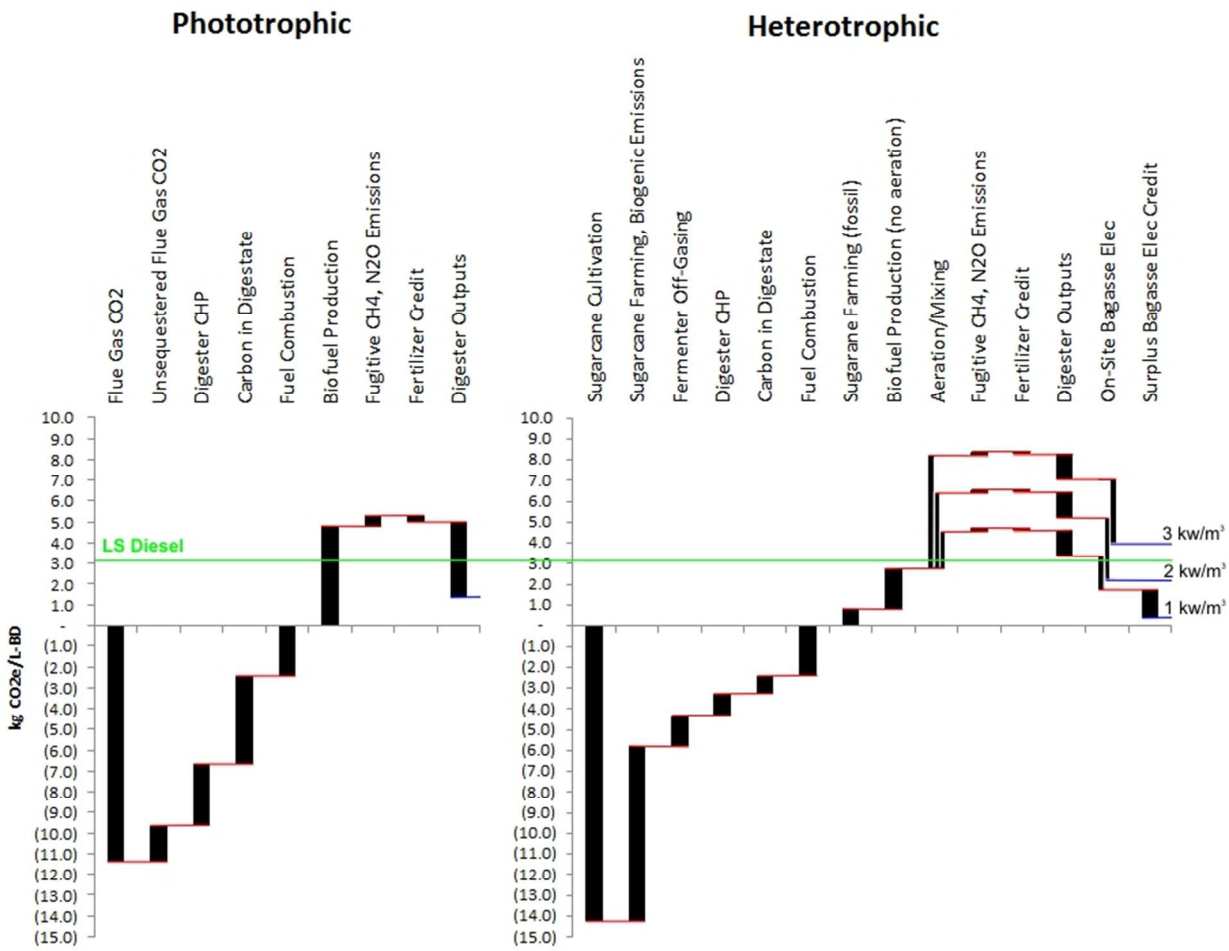


Figure S1 - The contributions to the global warming potential (GWP) for two of the three pathways are illustrated in the above waterfall plot. Bars shown in the negative portion of the plots indicate biogenic carbon emissions, which balance to zero upon combustion of the fuel. Bars shown in the positive portion of the plots represent the anthropogenic emissions that contribute to the fuel's net carbon footprint. Three reactor technology scenarios (1, 2, & 3 kW/m^3 for aeration/mixing) are illustrated for the heterotrophic pathway (right), illustrating the significance of these assumptions on the results. These plots do not include impacts from indirect land use change (ILUC).

Biomass Composition

The composition of the algal biomass is important for a number of reasons. Most importantly, the lipid fraction of the algae determines how much biomass must be cultivated to produce the functional unit of algal biodiesel. A higher lipid fraction therefore implies that less nutrients and infrastructure is required (and hence less upstream embodied and operational

energy). Another consequence, however, is that after the lipid has been extracted there is less lipid extracted algae (LEA) leftover for energy recovery via anaerobic digestion.

The distribution of the macromolecules (protein, carbohydrates, and lipids) was based on Frank et al. (2011) for the phototrophic and heterotrophic biomass (or the "baseline" and "high lipid" scenarios, respectively)[1]. The hybrid scenario, which contains 55wt% lipid rather than the 50wt% lipid selected for the heterotrophic biomass, was approximated by keeping the same 1:1 protein to carbohydrate ratio for the non-lipid portion. The macromolecule approximations of $C_{40}H_{74}O_5$ for lipid, $C_{4.43}H_7O_{1.44}N_{1.16}$ for protein, and $C_6H_{12}O_6$ for carbohydrate were based on Lardon et al. (2009)[2]. Although phosphorus is not represented in these formulae, a 10:1 ratio (by mass) of N:P was assumed, as recommended by the authors. A summary of these results is shown in Table S1 and Figure S2.

Table S1 - Biomass composition assumptions for the three pathways, on an ash-free dry weight basis.

		Phototrophic	Heterotrophic	Hybrid
Macromolecule Composition				
Lipid:	$C_{40}H_{74}O_5$	25.0%	50.0%	55.0%
Protein:	$C_{4.43}H_7O_{1.44}N_{1.16}$	50.0%	25.0%	22.5%
Carbohydrate:	$C_6H_{12}O_6$	25.0%	25.0%	22.5%
Elemental Composition				
C		54.68%	60.69%	62.18%
H		7.96%	9.18%	9.43%
O		27.59%	25.21%	23.96%
N		7.99%	4.03%	3.63%
P		1.77%	0.89%	0.80%
	Total:	**100.00%**	**100.00%**	**100.00%**

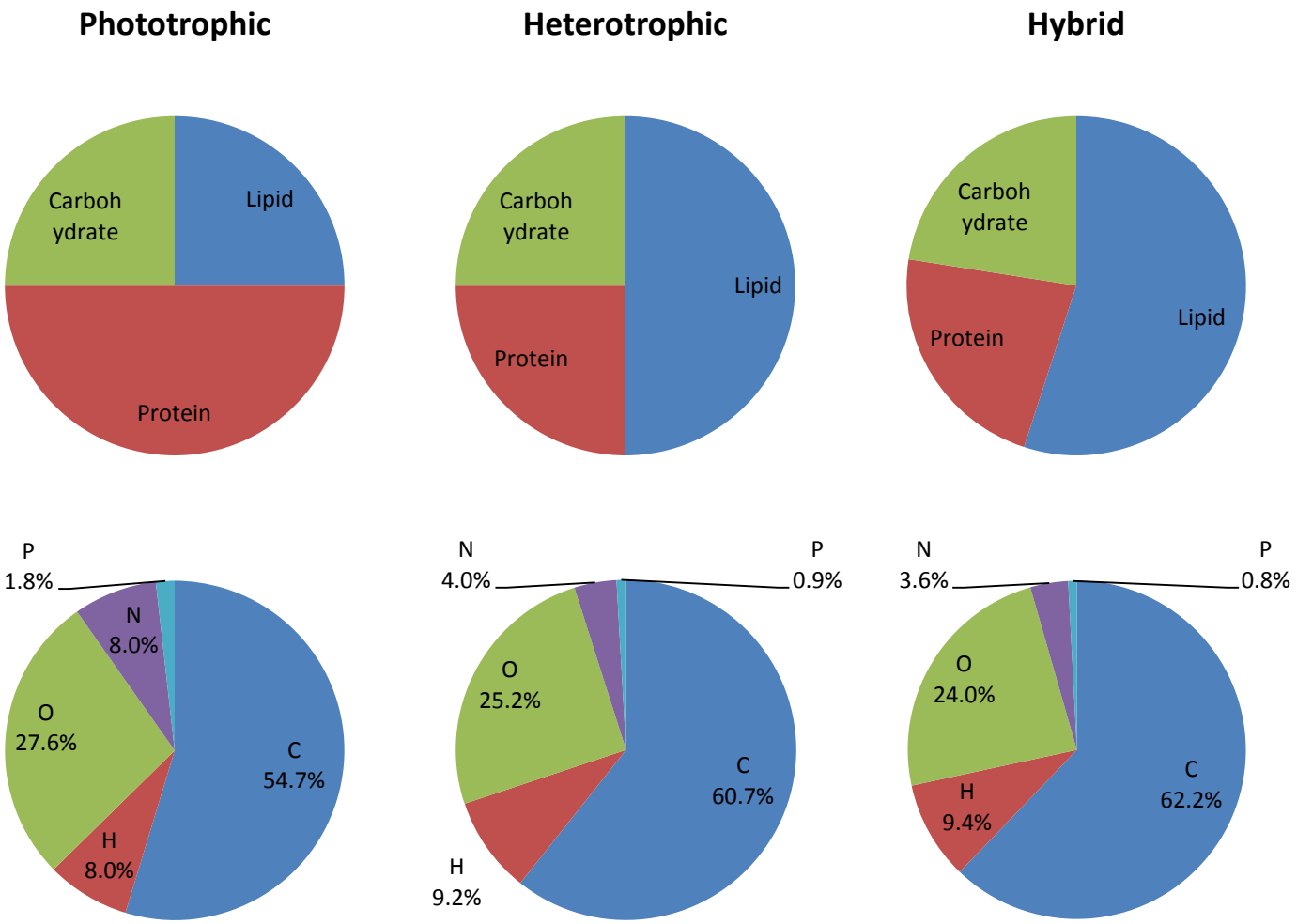


Figure S2 - Biomass composition assumptions for the three pathways.

Weighting Factors for Phototrophic Pathway

One of the key variables used to determine the water stress impact of the phototrophic pathway is the rate of evaporation, as this determines the amount of make-up water that must be pumped into the pond to maintain the appropriate volume. The national data set used in this analysis was produced by the National Oceanic and Atmospheric Administration[4]. The agency did not provide a continuous coverage layer with predicted evaporation rates but rather reported empirical evaporation data recorded at several hundred weather stations across the

country. The locations of these sites were not established systematically, however, and therefore averaging the results from each of the locations would skew the results toward locations where the concentration of sites is higher. The sites are much closer together on the west coast, for example, than in the southeastern United States. To compensate for this non-uniform distribution, results from each of the sites were weighted according to the area of its Thiessen polygon. This approach assigns a polygon to each evaporation data site such that any location within that polygon is nearer to its associated point than to that of any other polygon[5]. These polygons are shown in Figure S3. The sites that are highlighted in red are those that meet the minimum average annual productivity of 20 $g \cdot m^{-2} \cdot day^{-1}$.

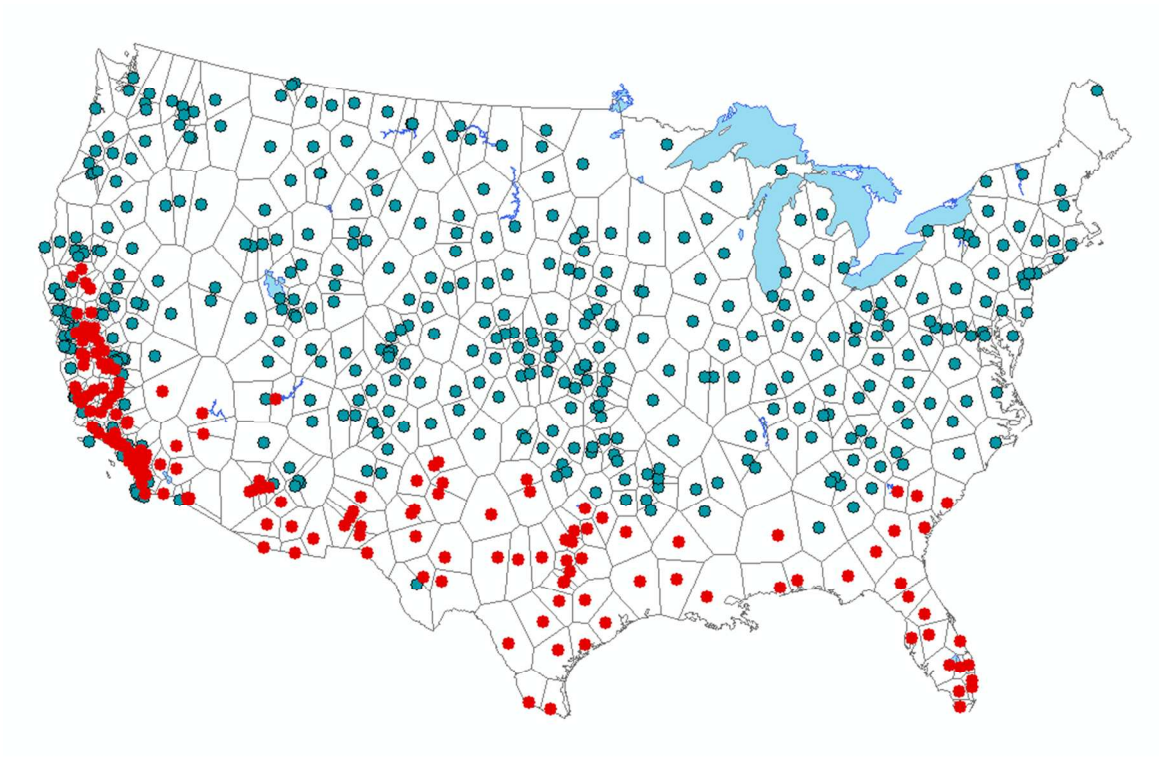


Figure S3 - The Thiessen polygons associated with the NOAA evaporation data sites are outlined above, trimmed by the perimeter of the contiguous United States. Locations highlighted in red are those that meet the minimum average annual phototrophic productivity cut-off of 20 $g \cdot m^{-2} \cdot day^{-1}$.

Impact Factors

A summary of the impact factors used in the analysis is included in Table S2. Recall that a geographic information systems (GIS) approach was used to explore the regional variations for the land use and water stress impact calculations based on yield data from the National Agricultural Statistics Service [6].

Table S2 - Impact factors applied to the inventory of material and energy flows for the three pathways. The denominator in the "Units" column indicates how each line item is inventoried.

Process/Input	Value	Units	Reference
Global Warming Potential			
Electricity, US Grid Average	0.216	kg CO_2e/MJ	[7]
Sugar, from sugarcane	0.222[α]	kg CO_2e/kg	[8]
Sugar, from sugar beet	0.505[β]	kg CO_2e/kg	[9]
N Fertilizer (urea, as N)	3.3	kg CO_2e/kg	[9]
P Fertilizer for cultivation, (diammonia phosphate, per mass P_2O_5)	1.57	kg CO_2e/kg	[9]
Methanol	0.556	kg CO_2e/kg	[7]
Hexane	0.898	kg CO_2e/kg	[9]
Natural Gas, combusted in industrial equipment	2.4	kg CO_2e/m^3	[7]
Methane emissions (fugitive), CH_4	25	kg CO_2e/kg	[10]
Nitrous Oxide emissions (field), N_2O (as N)	298	kg CO_2e/kg	[10]
Fossil Energy			
Electricity, US Grid Average	3.03	MJ/MJ	[7]
Sugar, from cane (biogenic emissions excluded)	1.834[α]	MJ/kg	[8]
Sugar, from beet (biogenic emissions excluded)	6.49[β]	MJ/kg	[9]
N Fertilizer (urea, as N) for phototrophic pathway	65.4	MJ/kg	[9]
P Fertilizer for cultivation, (diammonia phosphate, per mass P_2O_5)	22.12	MJ/kg	[9]
Methanol	35.44	MJ/kg	[7]
Hexane	60.89	MJ/kg	[9]
Natural Gas, combusted in industrial equipment	42.1	MJ/m^3	[7]
Land Use			
N Fertilizer (urea, as N) for phototrophic pathway	0.0856	m^2/kg	[9]
P Fertilizer for cultivation, (diammonia phosphate, per mass P_2O_5)	0.115	m^2/kg	[9]
Water Use			
Water consumption for electricity generation.	0.41[γ]	L/MJ	[11]

[α]Adapted from the year 2020 scenario.
[β]Sugar from sugar beet was modeled based on a refinery in Switzerland.
[γ]National weighted average for the United States.

Inventory Tables

Table S3 - A summary of the inventory of inputs required for the three pathways to produce 5 million liters of algal biodiesel annually. This table reflects the 1 kW/m^3 reactor aeration/mixing scenario with sugarcane as the feedstock. Recall that water inputs and land requirements were calculated independently based on a GIS analysis.

		Units	Seed Train	Pond Growth	Dewatering	Reactor Growth	Cell Separation	Oil Conversion	Digester Operation	Digester Output	Excess Bagasse Cogeneration Used Onsite	Total
PHOTOTROPHIC	Electrical Energy	MJ	-	23,234,447	27,747,001	-	14,711,782	470,725	13,948,774	(60,657,624)	-	19,455,104
	Heat Energy	MJ	-	-	-	-	48,989,207	9,087,036	15,597,104	(79,038,722)	-	-
	Sugar	kg	-	-	-	-	-	-	-	-	-	-
	N Fertilizer (Urea, as N)	kg	-	462,357	-	-	-	-	-	-	-	462,357
	P Fertilizer	kg P2O5	-	488,753	-	-	-	-	-	-	-	488,753
	Methanol	kg	-	-	-	-	-	440,392	-	-	-	440,392
	Hexane	kg	-	-	-	-	22,900	-	-	-	-	22,900
	Natural Gas	m3	-	-	-	-	1,628,089	301,995	518,348	(2,232,732)	-	215,701
HETEROTROPHIC	Electrical Energy	MJ	8,902,872	-	3,708,564	33,388,668	7,902,858	470,725	4,177,304	(20,698,088)	(37,852,902)	-
	Heat Energy	MJ	-	-	-	-	48,989,207	9,087,036	4,670,937	(26,970,236)	-	35,776,943
	Sugar	kg	5,150,784	-	-	15,452,351	-	-	-	-	-	20,603,135
	N Fertilizer (Urea, as N)	kg	24,887	-	-	99,548	-	-	-	-	-	124,435
	P Fertilizer	kg P2O5	26,308	-	-	105,232	-	-	-	-	-	131,539
	Methanol	kg	-	-	-	-	-	440,392	-	-	-	440,392
	Hexane	kg	-	-	-	-	22,900	-	-	-	-	22,900
	Natural Gas	m3	-	-	-	-	1,628,089	301,995	155,232	(761,871)	-	1,323,446
HYBRID	Electrical Energy	MJ	-	2,566,282	13,895,527	33,388,668	7,902,858	470,725	4,177,304	(20,698,088)	(41,703,274)	-
	Heat Energy	MJ	-	-	-	-	48,989,207	9,087,036	4,670,937	(26,970,236)	-	35,776,943
	Sugar	kg	-	-	-	18,027,743	-	-	-	-	-	18,027,743
	N Fertilizer (Urea, as N)	kg	-	89,659	-	-	-	-	-	-	-	89,659
	P Fertilizer	kg P2O5	-	94,777	-	-	-	-	-	-	-	94,777
	Methanol	kg	-	-	-	-	-	440,392	-	-	-	440,392
	Hexane	kg	-	-	-	-	22,900	-	-	-	-	22,900
	Natural Gas	m3	-	-	-	-	1,628,089	301,995	155,232	(761,871)	-	1,323,446

Table S4 - A summary of the inventory of inputs required for the three pathways to produce 5 million liters of algal biodiesel annually. This table reflects the 2 kW/m^3 reactor aeration/mixing scenario with sugarcane as the feedstock. Recall that water inputs and land requirements were calculated independently based on a GIS analysis.

		Units	Seed Train	Pond Growth	Dewatering	Reactor Growth	Cell Separation	Oil Conversion	Digester Operation	Digester Output	Excess Bagasse Cogeneration Used Onsite	Total
PHOTOTROPHIC	Electrical Energy	MJ	-	23,234,447	27,747,001	-	14,711,782	470,725	13,948,774	(60,657,624)	-	19,455,104
	Heat Energy	MJ	-	-	-	-	48,989,207	9,087,036	15,597,104	(79,038,722)	-	-
	Sugar	kg	-	-	-	-	-	-	-	-	-	-
	N Fertilizer (Urea, as N)	kg	-	462,357	-	-	-	-	-	-	-	462,357
	P Fertilizer	kg P2O5	-	488,753	-	-	-	-	-	-	-	488,753
	Methanol	kg	-	-	-	-	-	440,392	-	-	-	440,392
	Hexane	kg	-	-	-	-	22,900	-	-	-	-	22,900
	Natural Gas	m3	-	-	-	-	1,628,089	301,995	518,348	(2,232,732)	-	215,701
HETEROTROPHIC	Electrical Energy	MJ	17,803,426	-	3,708,564	66,765,746	7,902,858	470,725	4,177,304	(20,698,088)	(70,158,322)	9,972,212
	Heat Energy	MJ	-	-	-	-	48,989,207	9,087,036	4,670,937	(26,970,236)	-	35,776,943
	Sugar	kg	5,150,784	-	-	15,452,351	-	-	-	-	-	20,603,135
	N Fertilizer (Urea, as N)	kg	24,887	-	-	99,548	-	-	-	-	-	124,435
	P Fertilizer	kg P2O5	26,308	-	-	105,232	-	-	-	-	-	131,539
	Methanol	kg	-	-	-	-	-	440,392	-	-	-	440,392
	Hexane	kg	-	-	-	-	22,900	-	-	-	-	22,900
	Natural Gas	m3	-	-	-	-	1,628,089	301,995	155,232	(761,871)	-	1,323,446
HYBRID	Electrical Energy	MJ	-	2,566,282	13,895,527	66,765,746	7,902,858	470,725	4,177,304	(20,698,088)	(61,388,532)	13,691,821
	Heat Energy	MJ	-	-	-	-	48,989,207	9,087,036	4,670,937	(26,970,236)	-	35,776,943
	Sugar	kg	-	-	-	18,027,743	-	-	-	-	-	18,027,743
	N Fertilizer (Urea, as N)	kg	-	89,659	-	-	-	-	-	-	-	89,659
	P Fertilizer	kg P2O5	-	94,777	-	-	-	-	-	-	-	94,777
	Methanol	kg	-	-	-	-	-	440,392	-	-	-	440,392
	Hexane	kg	-	-	-	-	22,900	-	-	-	-	22,900
	Natural Gas	m3	-	-	-	-	1,628,089	301,995	155,232	(761,871)	-	1,323,446

Table S5 - A summary of the inventory of inputs required for the three pathways to produce 5 million liters of algal biodiesel annually. This table reflects the 3 kW/m^3 reactor aeration/mixing scenario with sugarcane as the feedstock. Recall that water inputs and land requirements were calculated independently based on a GIS analysis.

		Units	Seed Train	Pond Growth	Dewatering	Reactor Growth	Cell Separation	Oil Conversion	Digester Operation	Digester Output	Excess Bagasse Cogeneration Used Onsite	Total
PHOTOTROPHIC	Electrical Energy	MJ	-	23,234,447	27,747,001	-	14,711,782	470,725	13,948,774	(60,657,624)	-	19,455,104
	Heat Energy	MJ	-	-	-	-	48,989,207	9,087,036	15,597,104	(79,038,722)	-	-
	Sugar	kg	-	-	-	-	-	-	-	-	-	-
	N Fertilizer (Urea, as N)	kg	-	462,357	-	-	-	-	-	-	-	462,357
	P Fertilizer	kg P2O5	-	488,753	-	-	-	-	-	-	-	488,753
	Methanol	kg	-	-	-	-	-	440,392	-	-	-	440,392
	Hexane	kg	-	-	-	-	22,900	-	-	-	-	22,900
	Natural Gas	m3	-	-	-	-	1,628,089	301,995	518,348	(2,232,732)	-	215,701
HETEROTROPHIC	Electrical Energy	MJ	26,703,980	-	3,708,564	100,142,824	7,902,858	470,725	4,177,304	(20,698,088)	(70,158,322)	52,249,845
	Heat Energy	MJ	-	-	-	-	48,989,207	9,087,036	4,670,937	(26,970,236)	-	35,776,943
	Sugar	kg	5,150,784	-	-	15,452,351	-	-	-	-	-	20,603,135
	N Fertilizer (Urea, as N)	kg	24,887	-	-	99,548	-	-	-	-	-	124,435
	P Fertilizer	kg P2O5	26,308	-	-	105,232	-	-	-	-	-	131,539
	Methanol	kg	-	-	-	-	-	440,392	-	-	-	440,392
	Hexane	kg	-	-	-	-	22,900	-	-	-	-	22,900
	Natural Gas	m3	-	-	-	-	1,628,089	301,995	155,232	(761,871)	-	1,323,446
HYBRID	Electrical Energy	MJ	-	2,566,282	13,895,527	100,142,824	7,902,858	470,725	4,177,304	(20,698,088)	(61,388,532)	47,068,899
	Heat Energy	MJ	-	-	-	-	48,989,207	9,087,036	4,670,937	(26,970,236)	-	35,776,943
	Sugar	kg	-	-	-	18,027,743	-	-	-	-	-	18,027,743
	N Fertilizer (Urea, as N)	kg	-	89,659	-	-	-	-	-	-	-	89,659
	P Fertilizer	kg P2O5	-	94,777	-	-	-	-	-	-	-	94,777
	Methanol	kg	-	-	-	-	-	440,392	-	-	-	440,392
	Hexane	kg	-	-	-	-	22,900	-	-	-	-	22,900
	Natural Gas	m3	-	-	-	-	1,628,089	301,995	155,232	(761,871)	-	1,323,446

Table S6 - A summary of the annual outputs for the three pathways assuming sugarcane is the feedstock.

			Aeration/Mixing Energy Scenario:		
		Units	**1 kW/m3**	**2 kW/m3**	**3 kW/m3**
PHOTOTROPHIC	Fugitive Methane	kg CH4	73,524	73,524	73,524
	Fugitive N2O	kg N2O-N	1,228	1,228	1,228
	Biodiesel	Liters	**5,000,000**	**5,000,000**	**5,000,000**
	N Fertilizer from Residue	kg N	122,831	122,831	122,831
	P2O5 Fertilizer from Residue	kg P2O5	396,440	396,440	396,440
	CO2 from biogas combustion	kg CO2	15,157,619	15,157,619	15,157,619
	CO2 from fermenter	kg CO2	-	-	-
	Bagasse Elec Generation (consumed on site)	MJ	-	-	-
	Surplus Bagasse Elec Generation	MJ	-	-	-
HETEROTROPHIC	Fugitive Methane	kg CH4	25,089	25,089	25,089
	Fugitive N2O	kg N2O-N	419	419	419
	Biodiesel	Liters	**5,000,000**	**5,000,000**	**5,000,000**
	N Fertilizer from Residue	kg N	41,913	41,913	41,913
	P2O5 Fertilizer from Residue	kg P2O5	135,276	135,276	135,276
	CO2 from biogas combustion	kg CO2	5,172,206	5,172,206	5,172,206
	CO2 from fermenter	kg CO2	7,292,813	7,292,813	7,292,813
	Bagasse Elec Generation (consumed on site)	MJ	70,158,322	70,158,322	70,158,322
	Surplus Bagasse Elec Generation	MJ	32,305,420	-	-
HYBRID	Fugitive Methane	kg CH4	25,089	25,089	25,089
	Fugitive N2O	kg N2O-N	419	419	419
	Biodiesel	Liters	**5,000,000**	**5,000,000**	**5,000,000**
	N Fertilizer from Residue	kg N	41,913	41,913	41,913
	P2O5 Fertilizer from Residue	kg P2O5	135,276	135,276	135,276
	CO2 from biogas combustion	kg CO2	5,172,206	5,172,206	5,172,206
	CO2 from fermenter	kg CO2	8,117,543	8,117,543	8,117,543
	Bagasse Elec Generation (consumed on site)	MJ	61,388,532	61,388,532	61,388,532
	Surplus Bagasse Elec Generation	MJ	19,685,258	-	-

Results for Different Scenarios

Table S7 – Sensitivity of net energy ratio (NER) results to open pond algae yield and heterotrophic cultivation batch length. Results are unitless.

Scenario	Yield (pond growth)	Batch Length (reactor growth)	Photo.	Heterotrophic			Hybrid		
				1 $kw \cdot m^{-3}$	2 $kw \cdot m^{-3}$	3 $kw \cdot m^{-3}$	1 $kw \cdot m^{-3}$	2 $kw \cdot m^{-3}$	3 $kw \cdot m^{-3}$
Low	12.5 $g \cdot m^{-2} \cdot day^{-1}$	4 days	0.94	1.66	1.48	0.95	1.69	1.55	1.10
Baseline	25 $g \cdot m^{-2} \cdot day^{-1}$	3 days	1.32	1.59	1.12	0.60	1.62	1.09	0.66
High	37.5 $g \cdot m^{-2} \cdot day^{-1}$	2 days	1.52	1.53	0.77	0.44	1.53	0.74	0.46

Table S8 – Sensitivity of global warming potential (GWP) results to open pond algae yield and heterotrophic cultivation batch length. Results are in units of kg $CO_2e \cdot L^{-1}$.

Scenario	Yield (pond growth)	Batch Length (reactor growth)	Photo.	Heterotrophic			Hybrid		
				1 $kw \cdot m^{-3}$	2 $kw \cdot m^{-3}$	3 $kw \cdot m^{-3}$	1 $kw \cdot m^{-3}$	2 $kw \cdot m^{-3}$	3 $kw \cdot m^{-3}$
Low	12.5 $g \cdot m^{-2} \cdot day^{-1}$	4 days	2.38	1.42	1.63	2.50	1.38	1.53	2.13
Baseline	25 $g \cdot m^{-2} \cdot day^{-1}$	3 days	1.70	1.48	2.14	3.86	1.45	2.16	3.52
High	37.5 $g \cdot m^{-2} \cdot day^{-1}$	2 days	1.48	1.56	3.05	5.22	1.54	3.14	4.95

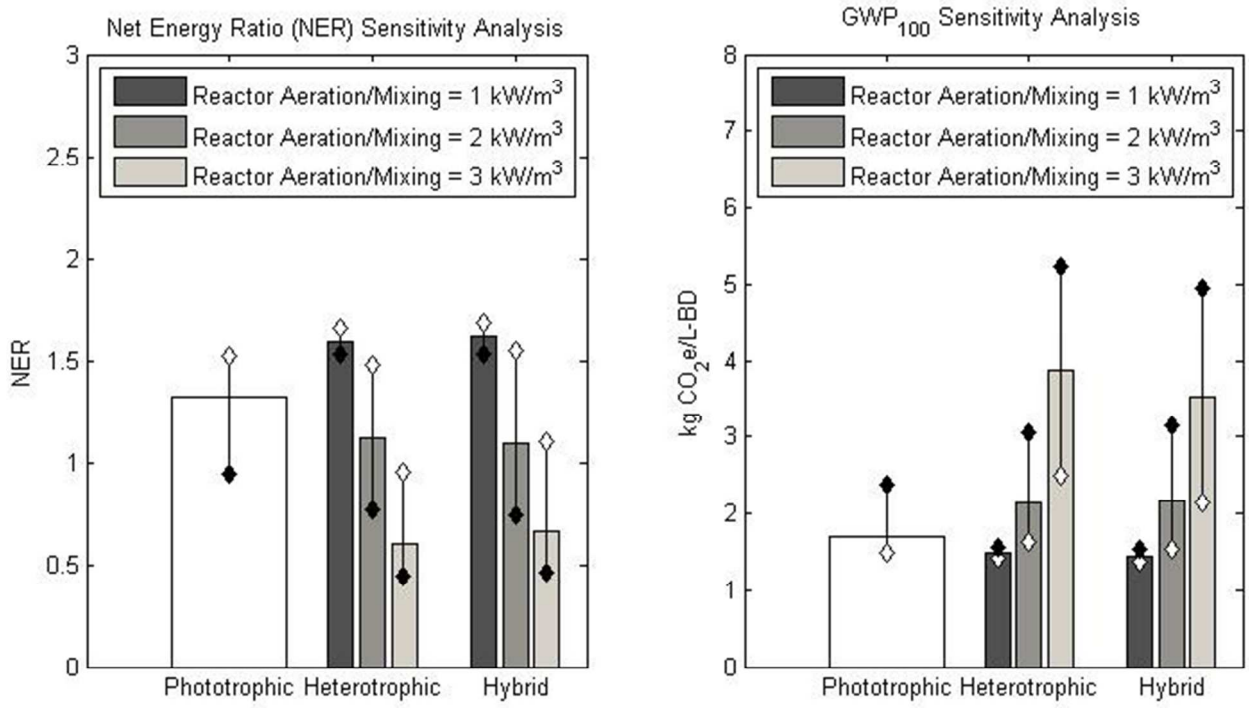
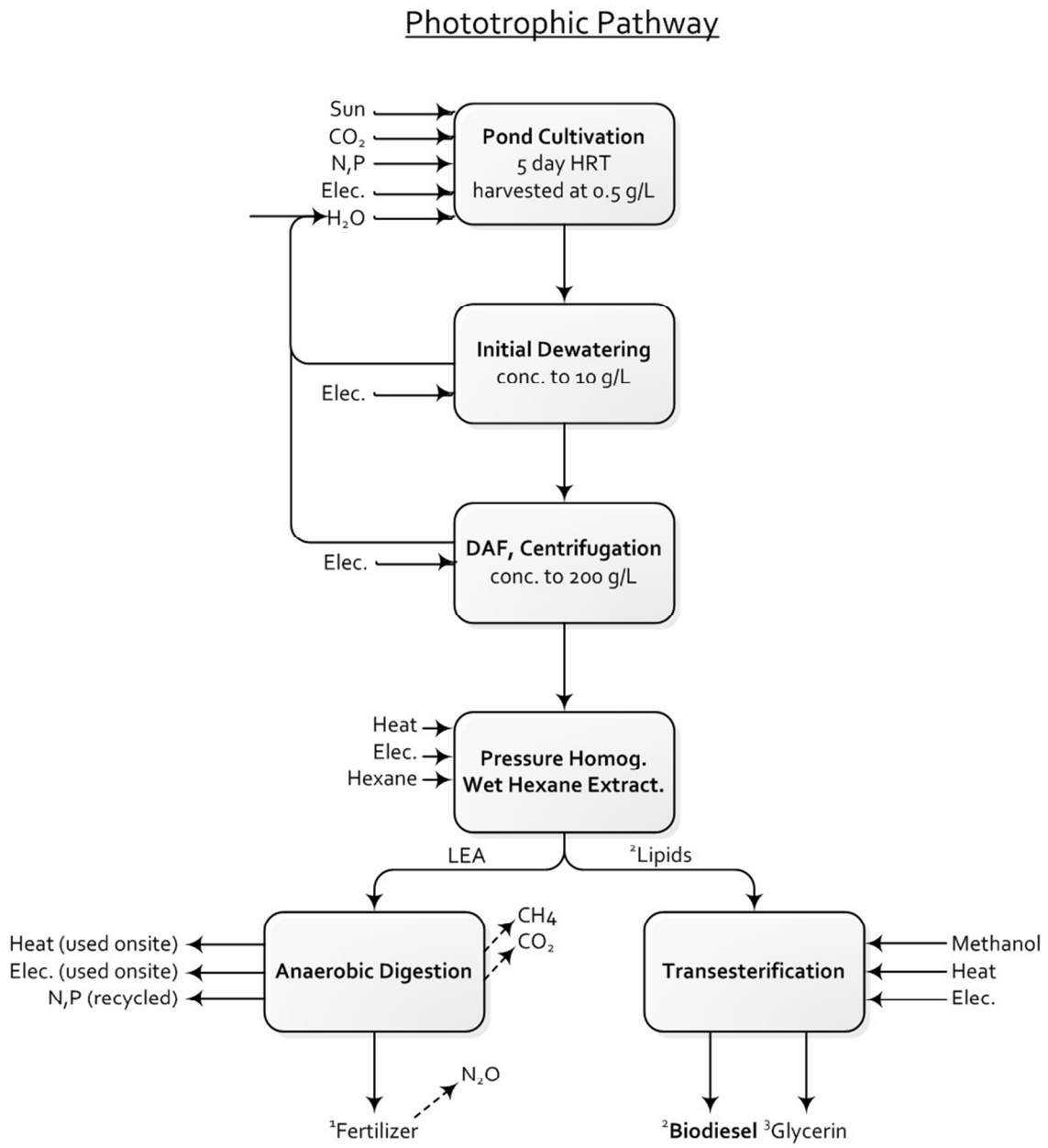


Figure S4 - Results of additional sensitivity analyses. The high performance scenario is marked with a white diamond, while the low performance scenario is marked with a black diamond.

Individual Pathway Flow Diagrams

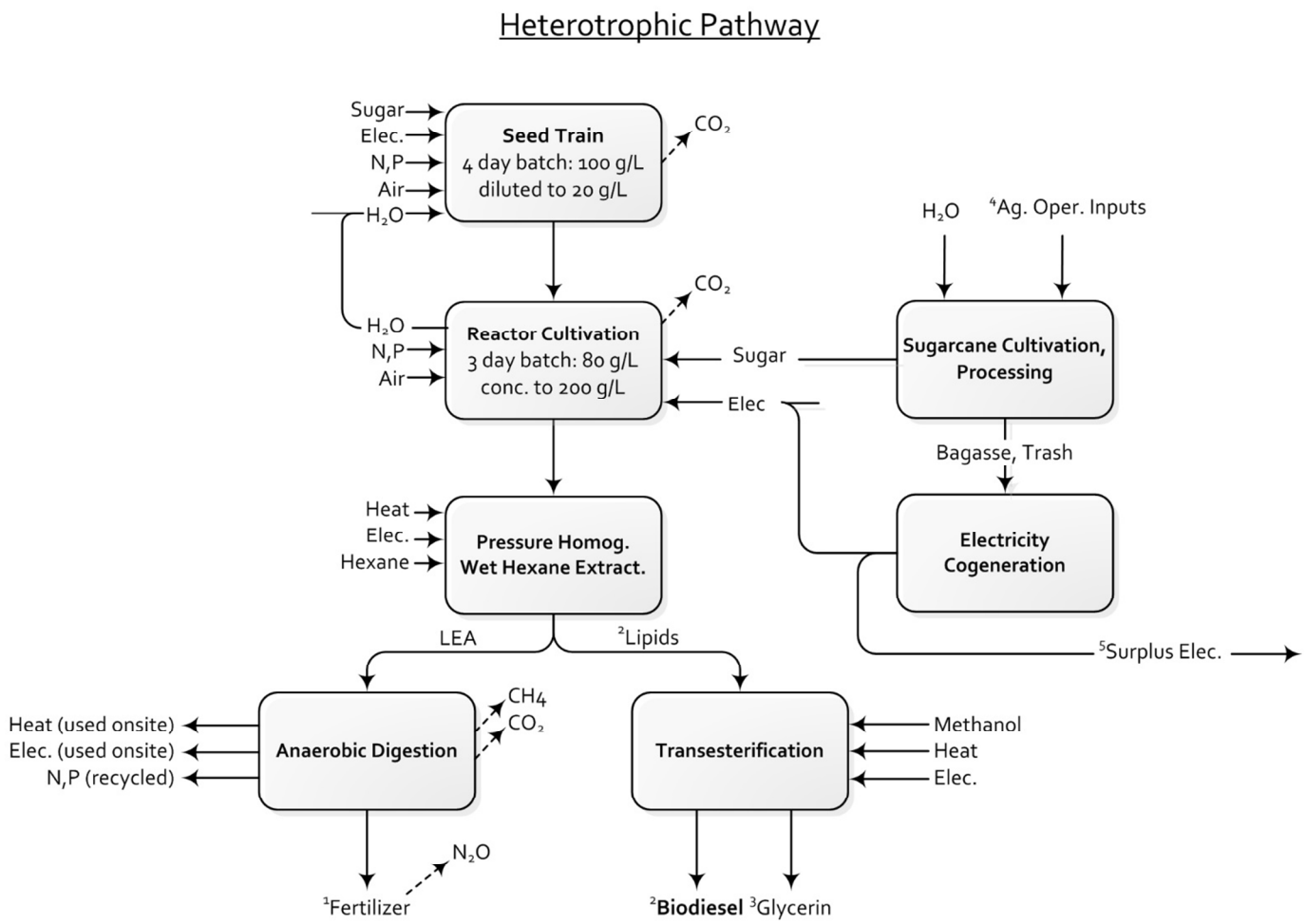


[1]Digestate residue is transported (contributing a burden) and then land applied for a fertilizer credit. A fraction of the nitrogen applied escapes as N2O which creates a burden. Co-product credit is calculated by displacement of fertilizer and the credit is applied toward lipid production.

[2]Transportation burdens are included, conforming to the same assumptions used in the GREET model.

[3]Glycerin is treated as a co-product which shares the burdens of lipid production with the biodiesel on an energy based allocation.

Figure S5 - Flow diagram for the phototrophic pathway.



[1]Digestate residue is transported (contributing a burden) and then land applied for a fertilizer credit. A fraction of the nitrogen applied escapes as N_2O which creates a burden. Co-product credit is calculated by displacement of fertilizer and the credit is applied toward lipid production. In the highest efficiency reactor cultivation scenario there is a surplus of co-generated electricity from combustion of sugarcane bagasse, which is exported to the grid. In this case the fertilizer credit is shared between the lipids and the electricity co-product on an energy based allocation.

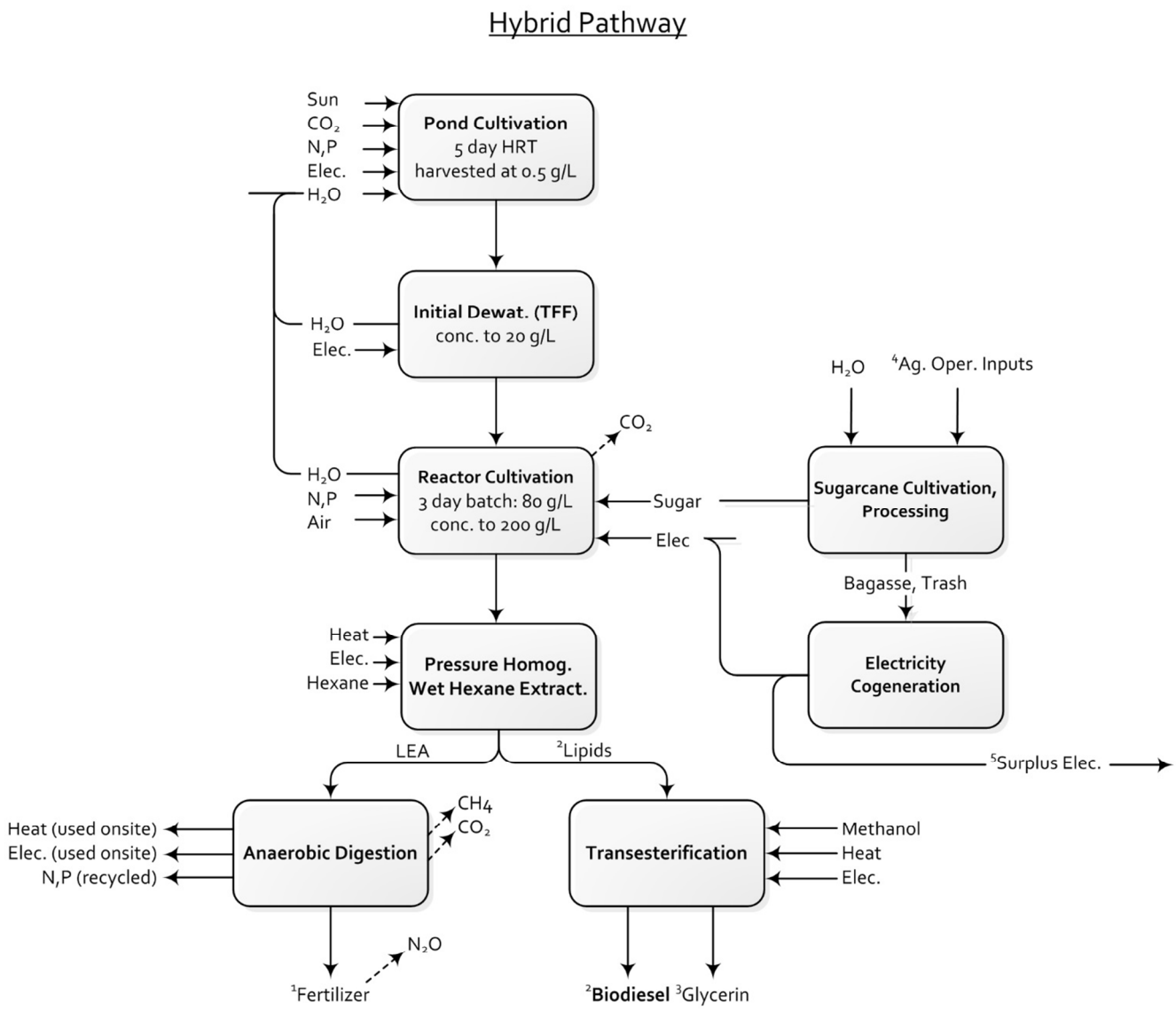
[2]Transportation burdens are included, conforming to the same assumptions used in the GREET model.

[3]Glycerin is treated as a co-product which shares the burdens of lipid production with the biodiesel on an energy based allocation.

[4]Life cycle impacts for the agricultural operations were adapted from the year 2020 scenario of: Macedo, I.; Seabra, J.; Silva, J. Greenhouse gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. Biomass and Bioenergy **2008**, 32, 582-595.

[5]The only scenario in which a surplus electricity co-product was observed was in the most efficient reactor technology case (1 kw/m^3). In the other two scenarios the electricity was used to avoid fossil energy consumption, but inputs were still required.

Figure S6 - Flow diagram for the heterotrophic pathway.



[1]Digestate residue is transported (contributing a burden) and then land applied for a fertilizer credit. A fraction of the nitrogen applied escapes as N_2O which creates a burden. Co-product credit is calculated by displacement of fertilizer and the credit is applied toward lipid production. In the highest efficiency reactor cultivation scenario there is a surplus of co-generated electricity from combustion of sugarcane bagasse, which is exported to the grid. In this case the fertilizer credit is shared between the lipids and the electricity co-product on an energy based allocation.

[2]Transportation burdens are included, conforming to the same assumptions used in the GREET model.

[3]Glycerin is treated as a co-product which shares the burdens of lipid production with the biodiesel on an energy based allocation.

[4]Life cycle impacts for the agricultural operations were adapted from the year 2020 scenario of: Macedo, I.; Seabra, J.; Silva, J. Greenhouse gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. Biomass and Bioenergy **2008**, 32, 582-595.

[5]The only scenario in which a surplus electricity co-product was observed was in the most efficient reactor technology case (1 kw/m^3). In the other two scenarios the electricity was used to avoid fossil energy consumption, but inputs were still required.

Figure S7 - Flow diagram for the hybrid pathway.

References

(1) Frank, E. D.; Han, J.; Palou-Rivera, I.; Elgowainy, A.; Wang, M. Q. *Life-Cycle Analysis of Algal Lipid Fuels with the GREET Model*; 2011.

(2) Lardon, L.; Hélias, A.; Sialve, B.; Steyer, J.-P.; Bernard, O. Life-Cycle Assessment of Biodiesel Production from Microalgae. *Environ. Sci. Technol.* **2009**, *43*, 6475–6481.

(3) Renouf, M. A.; Wegener, M. K.; Nielsen, L. K. An environmental life cycle assessment comparing Australian sugarcane with US corn and UK sugar beet as producers of sugars for fermentation. *Biomass and Bioenergy* **2008**, *32*, 1144–1155.

(4) Farnsworth, R. K.; Thompson, E. S. *Mean Monthly, Seasonal, and Annual Pan Evaporation for the United States*; Washington, D.C., 1982.

(5) Bolstad, P. *GIS Fundamentals: A first text on geographic information systems*; Third Edit.; Eider Press: White Bear Lake, MN, 2008; p. 620.

(6) USDA National Agricultural Statistics Service http://www.nass.usda.gov/.

(7) Nrel US Life Cycle Inventory Database http://www.nrel.gov/lci/.

(8) Macedo, I.; Seabra, J.; Silva, J. Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. *Biomass and Bioenergy* **2008**, *32*, 582–595.

(9) Frischknecht, R.; Jungbluth, N.; Althaus, H.-J.; Doka, G.; Dones, R.; Heck, T.; Hellweg, S.; Hischier, R.; Nemecek, T.; Rebitzer, G.; Spielmann, M. The ecoinvent Database: Overview and Methodological Framework (7 pp). *Int. J. Life Cycle Assess.* **2004**, *10*, 3–9.

(10) IPCC *Fourth Assessment Report: Climate Change 2007*; Solomon, S.; Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Averyt, K. B.; Tignor, M.; Miller, H. L., Eds.; Intergovernmental Panel on Climate Change, 2007; Vol. 4, pp. 213–252.

(11) Wu, M.; Peng, M. J. *Developing a Tool to Estimate Water Use in Electric Power Generation in the United States*; 2010.