Supporting Information for:

Assessing the Critical Role of Ecological Goods and Services In Microalgal Biofuel Life Cycles

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1. Model overview

In this study a hybrid EcoLCA model is developed to quantify the contribution of ecological resources within the algae-to-fuel supply chain, and to compare the resource intensity of producing microalgae renewable diesel and biodiesel to that of traditional petroleum diesel. Comprehensive hybrid LCA is performed on an integrated open raceway pond bio-refinery. Multiple biofuel production pathways are evaluated, consisting of a combination of CO_2 procurement, dewatering, drying, oil extraction, and coproduct scenarios. Process flows and life cycle inventories for algal biofuel production are constructed based on peer reviewed literature, heat and material balances, life cycle information, and best available engineering knowledge. A variety of energy return on investment metrics, sustainability indicators, and renewability indices based off of energy, exergy, and emergy analysis are used to quantify the consumption of ecological goods and services, environmental impacts, and resource intensity of producing microalgae fuels.

2. Biofuel production pathways

Two technological sets: *baseline* and *improved* biofuel production pathways are evaluated in this work. Baseline scenarios utilize current commercially proven technologies and process options for algae-to-fuel conversion, while improved scenarios consider technologies and process options that have yet to be proven commercially feasible. The examined biofuel production scenarios are tabulated in **Table S1.**

Table S1 - Baseline and Improved Biofuel Production Pathways

Production Pathways	CO2	Dewatering	Drying	Extraction	Residual Biomass
Baseline Scenario	MEA	Centrifugation	Natural Gas	Dry Extraction	Animal Feed (AF)
	MEA	Centrifugation	Natural Gas	Dry Extraction	Anaerobic Digestion (AD)
	MEA	Centrifugation	Natural Gas	Dry Extraction	Combined Heat & Power (CHP)
Improved Scenario	Flue Gas	Chamber Filter Press	Waste Heat[1]	Wet Extraction	Animal Feed (AF)
	Flue Gas	Chamber Filter Press	Waste Heat[1]	Wet Extraction	Anaerobic Digestion (AD)
	Flue Gas	Chamber Filter Press	Waste Heat[1]	Wet Extraction	Combined Heat & Power (CHP)

[1]Waste heat from a co-located power plant is utilized to dry the residual deoiled biomass (RDB) prior to combustion via CHP as well as algal derived biofertilizer, and animal feed prior to transportation.

3. Hybrid Ecologically Based Life Cycle Assessment

EcoLCA is a recent environmentally extended input-output life cycle oriented approach capable of accounting for the role of natural capital such as ecosystem goods and services in a life cycle framework. Eco-LCA considers a wide array of goods and services derived from nature and a hierarchical, thermodynamic-based resource aggregation scheme to permit meaningful interpretation [1]. EcoLCA was developed by researchers at the Ohio State University, and is available free of charge at http://resilience.eng.ohio-state.edu/eco-lca/

The hybrid Eco-LCA model developed in this study combines the 2002 Eco-LCA model of the US economy with detailed process level data[2]. This hybrid approach overcomes several of the shortcomings of traditional process LCA and Economic Input-Output (EIOLCA) [3].

4. Methodology

Steps in developing hybrid Eco-LCA

1.) Develop process scale inventory for fuel production pathways
2.) Determine the 2002 producer prices for economic inputs used in fuel production
3.) Quantify the 2002 economic activity for different industrial sectors via multiplying the mass and resources flows as developed in step (1) with their corresponding 2002 producer price as constructed in step (2)
4.) Input the economic activity for specific industrial sectors as developed in step (3) into EcoLCA to determine the energy, exergy, and emergy based resource consumption from these economic activities.
5.) Quantify direct ecological goods and services as well as fuel and energy products used in fuel production in regards to their energy, exergy and emergy.
6.) Combine the results from EcoLCA (step 4) with process level data (step 5) to calculate total ecological resource consumption on a life cycle basis

5. Process level inventory for microalgal biofuel production

Process inventory for an integrated microalgal ORP biorefinery operating in Phoenix, AZ was constructed based on prior research. A detailed description of the modeling assumptions, equations, and parameters can be found in ref[4, 5]. Mass, energy, and resources flows entering and leaving the product system for the renewable diesel production pathways evaluated in this analysis are provided in **Table S2.**

Table S2 - Process inventory for microalgal renewable diesel production

Parameters		Microalgal RD - Baseline Scenarios			Microalgal RD - Improved Scenarios		
Inputs	**Units**	**Animal Feed**	**Anaerobic Digestion**	**Combined Heat & Power**	**Animal Feed**	**Anaerobic Digestion**	**Combined Heat & Power**
Electricity	MJ	1.34E+08	1.41E+08	1.34E+08	8.99E+07	9.65E+07	8.99E+07
Natural Gas	m^3	2.59E+07	2.68E+07	2.59E+07	3.59E+05	1.32E+06	3.59E+05
Aluminum Sulfate	kg	6.40E+06	6.40E+06	6.40E+06	6.40E+06	6.40E+06	6.40E+06
Urea	kg	6.28E+06	3.77E+06	6.28E+06	6.28E+06	3.77E+06	6.28E+06
SSP	kg	2.39E+06	1.72E+06	2.39E+06	2.39E+06	1.72E+06	2.39E+06
KCL	kg	1.00E+06	1.00E+06	1.00E+06	1.00E+06	1.00E+06	1.00E+06
PVC	m^2	5.00E+05	5.00E+05	5.00E+05	5.00E+05	5.00E+05	5.00E+05
Wastewater	m^3	8.75E+06	8.75E+06	8.75E+06	8.75E+06	8.75E+06	8.75E+06
Hexane	kg	5.20E+04	5.20E+04	5.20E+04	3.38E+04	3.38E+04	3.38E+04
Hydrogen	kg	1.72E+05	1.72E+05	1.72E+05	1.68E+05	1.68E+05	1.68E+05
Petrolem Diesel	gal	2.64E+04	4.94E+03	4.23E+03	2.63E+04	4.84E+03	4.14E+03
Pipeline Transport	gal	2.64E+04	4.94E+03	4.23E+03	2.63E+04	4.84E+03	4.14E+03
Outputs	**Units**	**Animal Feed**	**Anaerobic Digestion**	**Combined Heat & Power**	**Animal Feed**	**Anaerobic Digestion**	**Combined Heat & Power**
Animal Feed (soybean meal eq.)	kg	2.82E+07	0.00E+00	0.00E+00	2.82E+07	0.00E+00	0.00E+00
Electricity	MJ	0.00E+00	8.39E+07	7.86E+07	0.00E+00	8.39E+07	7.86E+07
Biofertilizer (Urea eq.)	kg	0.00E+00	8.28E+05	0.00E+00	0.00E+00	8.28E+05	0.00E+00
Biofertilizer (SSP eq.)	kg	0.00E+00	6.73E+04	0.00E+00	0.00E+00	6.73E+04	0.00E+00
Heat (NG eq.)	m^3	0.00E+00	0.00E+00	5.67E+06	0.00E+00	0.00E+00	5.67E+06
Propane (LPG eq.)	kg	3.17E+05	3.17E+05	3.17E+05	3.10E+05	3.10E+05	3.10E+05
Renewable Diesel	kg	5.38E+06	5.38E+06	5.38E+06	5.26E+06	5.26E+06	5.26E+06

6. Producer price for economic inputs/outputs in microalgal renewable diesel production

The Eco-LCA model is developed based on a 2002 input-output (IO) model of the US economy. In this model, the US economy is aggregated into over 488 different economic sectors. In Eco-LCA the final demand (economic activity) in each of the economic sectors is translated into ecological and natural resource consumption. As such, the 2002 producer price for economic inputs used in algal biofuel production must be obtained to properly account for the consumption of ecological resources in algal-fuel production. **Table S3** provides the price data for economic inputs used in microalgal RD production.

Table S3 - Price data for economic inputs/outputs for microalgal renewable diesel production

Economic Inputs and Outputs in Microalgal Renewable Diesel Production						
Material or Energy Input/Output	**Sector Name**	**NAICS Code**	**Year**	**Unit**	**$/Unit**	**Source**
Inputs						
Electricity	Electricity Power Generation	221100	2002	MJ	1.36E-02	ref[6]
Natural Gas	Natural Gas Distribution	221200	2002	m^3	1.42E-01	ref[7]
Aluminum Sulfate	All other basic inorganic chemical manufacturing	325188	2000	kg	2.97E-01	ref[8]
Urea	Fertilizer Manufacturing	325310	2002	kg	2.11E-01	ref[9]
Superphosphate (SSP)	Fertilizer Manufacturing	325310	2002	kg	2.44E-01	ref[9]
Potassium Chloride (KCl)	Fertilizer Manufacturing	325310	2002	kg	1.81E-01	ref[9]
PVC	Plastics Material and Resin Manufacturing	325211	1999	m^2	2.58E+00	ref[10]
Wastewater	Water, Sewage and Other Systems	221300	2003	m^3	2.94E-02	ref[11]
Hexane	Other Basic Organic Chemical Manufacturing	325190	2003	kg	5.57E-01	ref[12]
Hydrogen	Industrial Gas Manufacturing	325120	2010	kg	1.50E+00	ref[13]
Diesel	Petroleum Refineries	324110	1997	gal	5.75E-01	ref[3]
Diesel	Pipeline Transportation	486000	2006	gal	2.30E-02	ref[14]
Coproducts						
Animal Feed (soybean meal eq.)	Other animal food manufacturing	311119	2002	kg	1.84E-01	Note*
Electricity	Electricity Power Generation	221100	2002	MJ	1.36E-02	ref[6]
Biofertilzier (Urea eq.)	Fertilizer Manufacturing	325310	2002	kg	2.11E-01	ref[9]
Biofertilzier (SSP eq.)	Fertilizer Manufacturing	325310	2002	kg	2.44E-01	ref[9]
Heat (NG eq.)	Natural Gas Distribution	221200	2002	m^3	1.42E-01	ref[7]
Propane (LGP eq.)	Petroleum Refineries	324110	2002	kg	2.46E-01	ref[15]

*Price of algal derived animal feed was based off of the market value of soybean meal estimated from http://www.indexmundi.com/commodities/?commodity=soybean-meal&months=12

An inflation calculator is used when 2002 price data cannot be obtained[16]. The inflation ratio is provided in **Table S4.** Furthermore, the inflation calculator can be accessed in the following link: http://www.bls.gov/data/inflation_calculator.htm

Table S4 - Inflation Ratio

Year	**Inflation Ratio** (Relative to 2002)
1997	1.12
1998	1.10
1999	1.08
2000	1.04
2001	1.02
2002	1.00
2003	0.98
2004	0.95
2005	0.92
2006	0.89

2007	0.87
2008	0.84
2009	0.84
2010	0.83

To obtain 2002 price data for economic inputs and outputs in microalgal RD production the market value of economic inputs (**Table S3**) was multiplied by the corresponding inflation ratio as shown in **Table S4;** the results are provided in **Table S5.**

Table S5 - 2002 Price data for economic inputs and outputs in microalgal renewable diesel production

Material or Energy Product	Sector Name	NAICS Code	Unit	$2002 /Unit
Inputs				
Electricity	Electricity and Power Generation	221100	MJ	1.36E-02
Natural Gas	Natural Gas Distribution	221200	m^3	1.42E-01
Aluminum Sulfate	All other basic inorganic chemical manufacturing	325188	kg	3.10E-01
Urea	Fertilizer Manufacturing	325310	kg	2.11E-01
SSP	Fertilizer Manufacturing	325310	kg	2.44E-01
KCL	Fertilizer Manufacturing	325310	kg	1.81E-01
PVC	Plastics Material and Resin Manufacturing	325211	m^2	2.79E+00
Wastewater	Water, Sewage and Other Systems	221300	m^3	2.87E-02
Hexane	Other Basic Organic Chemical Manufacturing	325190	kg	5.45E-01
Hydrogen	Industrial Gas Manufacturing	325120	kg	1.24E+00
Diesel	Petroleum Refineries	324110	gal	6.44E-01
Diesel	Pipeline Transportation	486000	gal	2.05E-02
Coproducts				
Animal Feed (soybean meal eq.)	Other animal food manufacturing	311119	kg	1.84E-01
Electricity	Electricity Power Generation	221100	MJ	1.36E-02
Biofertilzier (Urea eq.)	Fertilizer Manufacturing	325310	kg	2.11E-01
Biofertilzier (SSP eq.)	Fertilizer Manufacturing	325310	kg	2.44E-01
Heat (NG eq.)	Natural Gas Distribution	221200	m^3	1.42E-01
Propane (LPG eq.)	Petroleum Refineries	324110	kg	2.46E-01

The economic input(s) and output(s) from **Table S5** are aggregated into their corresponding industrial sector(s). The results of data aggregation are provided **in Table S6.**

Table S6 - Economic Activity ($ 2002) for industrial sectors used in microalgal renewable diesel production

Parameters	**Microalgae RD - Baseline Scenarios**			**Microalgal RD - Improved Scenarios**		
Sector Name	AF	AD	CHP	AF	AD	CHP
Inputs						
Electricity and Power Generation	1.82E+06	1.91E+06	1.82E+06	1.22E+06	1.31E+06	1.22E+06
Natural Gas Distribution	3.67E+06	3.81E+06	3.67E+06	5.10E+04	1.87E+05	5.10E+04

All other basic inorganic chemical manuf.	1.98E+06	1.98E+06	1.98E+06	1.98E+06	1.98E+06	1.98E+06
Fertilizer Manufacturing	2.09E+06	1.39E+06	2.09E+06	2.09E+06	1.39E+06	2.09E+06
Plastics Material and Resin Manufacturing	1.39E+06	1.39E+06	1.39E+06	1.39E+06	1.39E+06	1.39E+06
Water, Sewage and Other Systems	2.51E+05	2.51E+05	2.51E+05	2.51E+05	2.51E+05	2.51E+05
Other Basic Organic Chemical Manufacturing	2.83E+04	2.83E+04	2.83E+04	1.84E+04	1.84E+04	1.84E+04
Industrial Gas Manufacturing	2.13E+05	2.13E+05	2.13E+05	2.08E+05	2.08E+05	2.08E+05
Petroleum Refineries	1.70E+04	3.18E+03	2.73E+03	1.70E+04	3.12E+03	2.66E+03
Pipeline Transportation	5.41E+02	1.01E+02	8.67E+01	5.39E+02	9.91E+01	8.47E+01
Coproducts						
Other animal food manufacturing	5.19E+06	0.00E+00	0.00E+00	5.19E+06	0.00E+00	0.00E+00
Electricity Power Generation	0.00E+00	1.14E+06	1.07E+06	0.00E+00	1.14E+06	1.07E+06
Fertilizer Manufacturing	0.00E+00	1.91E+05	0.00E+00	0.00E+00	1.91E+05	0.00E+00
Natural Gas Distribution	0.00E+00	0.00E+00	8.06E+05	0.00E+00	0.00E+00	8.06E+05
Petroleum Refineries	7.81E+04	7.81E+04	7.81E+04	7.64E+04	7.64E+04	7.64E+04

7. Eco-LCA results for microalgal renewable diesel production

The EcoLCA model translates the economic activity in industrial sectors into natural resource consumption. EcoLCA quantifies the Energy, ICEC, and ECEC consumption per unit throughput of economic activity for a specific industrial sector. The Energy, ICEC, and ECEC to money ratios for the industrial sectors utilized in microalgal renewable diesel production are presented in **Table S7.**

Table S7 - Energy, ICEC, and ECEC to Price ($2002) ratios for industrial sectors

Sector Name	**NAICS Code**	**[1]Energy/ $**	**[2]ICEC/ $**	**[3]ECEC/ $**
Electricity and Power Generation	221100	1.30E+08	1.41E+08	1.02E+13
Natural Gas Distribution	221200	7.56E+06	8.08E+06	1.08E+12
All other basic inorganic chemical manufacturing	325188	2.80E+07	5.01E+07	1.48E+13
Fertilizer Manufacturing	325310	8.01E+07	8.59E+07	1.25E+13
Plastics Material and Resin Manufacturing	325211	9.36E+07	1.01E+08	9.61E+12
Water, Sewage and Other Systems	221300	1.69E+06	1.93E+06	3.33E+12
Other Basic Organic Chemical Manufacturing	325190	6.58E+07	7.12E+07	7.24E+12
Industrial Gas Manufacturing	325120	2.54E+07	3.27E+07	5.40E+12
Petroleum Refineries	324110	1.88E+07	1.99E+07	7.36E+08
Pipeline Transportation	486000	7.15E+06	7.74E+06	9.17E+08
Other animal food manufacturing	**311119**	2.12E+07	2.30E+07	5.35E+12

[1] Units – Non-renewable energy (joules) per unit 2002 dollar
[2] Units – Non-renewable exergy (joules) per unit 2002 dollar
[3] Units - Solar equivalent joules (sej) per unit 2002 dollar

Energy, ICEC, and ECEC consumption obtained via EcoLCA was calculated by multiplying the results from **Table S6** with their corresponding Energy, ICEC, and ECEC to price ratio(s) given in **Table S7**. The results are provided in **Table S8.**

Table S8 - Energy, ICEC, and ECEC consumption obtained via EcoLCA

Parameters	Microaglal RD - Baseline Scenarios			Microalgal RD - Improved Scenarios		
Coproduct Scenarios	AF	AD	CHP	AF	AD	CHP
Inputs						
Non-Renewable Energy	6.26E+14	5.83E+14	6.26E+14	5.20E+14	4.77E+14	5.19E+14
Non-Renewable ICEC	7.15E+14	6.69E+14	7.15E+14	6.01E+14	5.55E+14	6.00E+14
ECEC	9.37E+19	8.61E+19	9.36E+19	8.36E+19	7.59E+19	8.35E+19
Coproducts						
Non-Renewable Energy	1.12E+14	1.65E+14	1.47E+14	1.12E+14	1.65E+14	1.47E+14
Non-Renewable ICEC	1.21E+14	1.78E+14	1.58E+14	1.21E+14	1.78E+14	1.58E+14
ECEC	2.79E+19	1.42E+19	1.20E+19	2.79E+19	1.42E+19	1.20E+19

8. Direct ecological goods and services (EGS) and the use phase of energy/fuel products in microalgal renewable diesel production

EcoLCA does not consider the use phase of energy and fuel products or direct ecological good and services that are consumed at the process scale. Therefore, data from the process scale must be added to the results obtained via EcoLCA.

8.1. Direct Ecological Goods and Services:

Direct ecological goods and services (EGS) considered in algal RD production include solar insolation (sunlight), freshwater, and photosynthetic CO2. The energy and material flows for direct EGS are provided in **Table S9.** Furthermore, the energy, exergy, and transformity of direct EGS are provided in **Table S10.**

Table S9 - Direct Ecological Goods and Services in Microalgal biofuel production

Direct EGS	Unit	Microalgal RD - Baseline Scenarios	Microalgal RD - Improved Scenarios
Solar Insolation[1]	Joule	3.01E+15	3.01E+15
Solar Insolation (Metabolised)	Joule	6.03E+13	6.03E+13
Atmospheric Carbon[2]	Grams	1.59E+10	1.59E+10
Freshwater[2]	Grams	1.11E+13	1.10E+13

[1]ref[17]
[2]Based on process calculations

Table S10 - Energy, Exergy, and Transformity of direct EGS in microalgal biofuel production

Direct EGS	Unit	Energy (j) /Unit	Exergy (j) /Unit	Transformity (sej/unit)
Solar Insolation	joule	1	1	1
Photosynthetic CO_2	grams carbon	N/A	N/A	103992000
Freshwater	grams	N/A	4.94	202540

The energy, exergy, and emergy of Direct EGS used in biofuel production were calculated via multiplying the resources flows as expressed in **Table S9** with their corresponding energy, exergy, and transformity given in **Table S10.** The results are provided in **Table S11.**

Table S11 - Energy, exergy, and emergy of direct EGS used in biofuel production

Parameters	**Microalgal RD - Baseline Scenarios**			**Microalgal RD - Improved Scenarios**		
Direct EGS	Energy*	Exergy*	Emergy	Energy*	Exergy*	Emergy
Solar Insolation	6.03E+13	6.03E+13	3.01E+15	6.03E+13	6.03E+13	3.01E+15
Photosynthetic CO2	N/A	N/A	1.65E+18	N/A	N/A	1.65E+18
Freshwater	N/A	5.47E+13	2.24E+18	N/A	5.42E+13	2.22E+18

*Only metabolized sunlight was considered for energy and exergy analysis

8.2. Use Phase of Energy and Fuel Products

The specific energy, exergy, and transformity of fuel and energy products used in biofuel production are provided in **Table S12.**

Table S12 - Energy, Exergy, and Transformity of fuel and Energy Products

Parameters	**Unit**	**Density**	**Unit**	**Energy**	**Exergy**	**Unit**	**Transformity**
Gasoline	kg/gal	2.78E+00	MJ/kg	[2]44.8	[2]48.3	sej/j	[6]111000
Diesel	kg/gal	3.18E+00	MJ/kg	[2]43.3	[2]44.4	sej/j	*111000
LPG	kg/gal	2.05E+00	MJ/kg	[2]47.3	[2]48.8	sej/j	*111000
Natural Gas	kg/scf	1.88E-02	MJ/kg	[3]55.1	[2]50.7	sej/j	[6]80600
Electricity[1]	-	-	MJ/MJ	2.4	2.8	sej/j	165542
Coal	-	-	MJ/kg	[3]20.6	[4]29	sej/j	[6]67200
Crude Oil	-	-	MJ/kg	[3]42.686	[5]46.2	sej/j	[6]90700
Nuclear	-	-	TJ/kg-U235	[7]79.5	[7]75.0	sej/g	[6]1880000000
Hydro	-	-	J/J	1	1	sej/j	[6]46643
Wind	-	-	J/J	1	1	sej/j	[6]2510
Geothermal	-	-	J/J	1	1	sej/j	[6]10200

[1]EcoLCA does not consider the feedstock energy consumed in electricity production (i.e. the combustion of coal, natural gas, etc.). The energy, exergy, and transformity of electricity was developed based on the 2002 U.S. average electricity mix and electricity generation efficiency. (See below for specific details)
[2]ref[18]
[3]ref[19]
[4]ref[20]
[5]ref[21]
[6]ref [22]
[7]ref[23]
[*]The transformity of Diesel and LPG was assumed to be equivalent to gasoline [3]

To determine the energy, exergy, and emergy of natural resources consumed in the production of 1 MJ of electricity, it was first necessary to quantify the high and low estimates for electricity conversion by primary energy resource type and quantify the U.S. 2002 electricity generation mix. This data is provided in **Table S13.**

Table S13 - 2002 U.S. Electricity generation mix and electricity generation conversion efficiencies

Primary Energy Resources	2002 U.S. Electricity Generation Mix (%)	Conversion Efficiency[1] % (Upper bound)	Conversion Efficiency[1] % (Lower bound)	Avg
Coal	52.0	47	39	43
Crude Oil	2.5	44	38	41
Natural Gas	16.5	-	-	39
Nuclear	21.0	36	33	34.5
Hydroelectricity	7.3	95	90	92.5
Wind	0.3	-	-	35
Geothermal	0.4	-	-	15

[1] ref[24]

The amount of each primary resources (J) required to produce 1 J of electricity was calculated by taking the ratio (1 / conversion efficiency). The results are shown in **Table S14**. The results should be interpreted as follows: on average it takes 2.3 J of coal to produce 1 J of coal-electricity. Additionally, it takes approximately 2.5 J of crude oil to produce 1 J of crude-oil derived electricity. The same interpretation applies to the other primary energy resources. The amount of each primary resource required to produce 1 J of the 2002 avg. electricity mix is given by the weighted average column shown in **Table S14.**

Table S14 - Amount of each primary resource (J) required to produce 1 J of electricity based on the 2002 avg. electricity mix

Primary Energy Resource	Lower Bound	Upper Bound	Average	Weighted Average (Avg x Gen. Mix)
Coal	2.6	2.1	2.3	1.22
Crude Oil	2.6	2.3	2.5	0.06
Natural Gas	-	2.6	2.6	0.42
Nuclear	3.0	2.8	2.9	0.61
Hydroelectricity	1.1	1.1	1.1	0.08
Wind	-	2.9	2.9	0.01
Geothermal	-	6.7	6.7	0.03

Direct primary energy resources consumed in the production of 1 J of electricity based on the 2002 U.S. electricity mix was calculated via multiplying the weighted average as obtained in **Table S14** with the specific exergy and transformity values shown in **Table S12.** The results are provided in **Table S15.**

Table S15 - Direct primary energy resources consumed in the production of 1 J of electricity based on the 2002 U.S. electricity mix. Consumption is reported in terms of energy, exergy, and emergy.

Parameters	Coal	Crude Oil	NG	Nuclear	Hydro	Wind	Geothermal	Total
Energy (J)	1.22E+00	6.13E-02	4.23E-01	6.10E-01	7.90E-02	8.57E-03	2.67E-02	2.43
Exergy (J)	1.56E+00	6.64E-02	4.53E-01	5.75E-01	7.90E-02	8.57E-03	2.67E-02	2.77
Emergy (sej)	1.05E+05	6.02E+03	3.65E+04	1.44E+04	3.68E+03	2.15E+01	2.72E+02	1.66E+05*

*Based on the analysis, the transformity of electricity is approximately 1.66 x 10^5 sej/J-electricity for the 2002 U.S. generation mix.

The use phase of energy/fuel products in biofuel production were accounted for via multiplying the resources flows of electricity, natural gas, diesel, propane, etc. as developed in **Table S2** with their corresponding specific energy, exergy, and transformity values given in **Table S12**. The results are provided in **Table S16.**

Table S16 - Use phase of energy/fuel products in biofuel production

Parameters	**Microalgal RD - Baseline Scenarios**			**Microalgal RD - Improved Scenarios**		
Coproduct Scenarios	AF	AD	CHP	AF	AD	CHP
Inputs						
Non-Renewable Energy	1.32E+15	1.37E+15	1.32E+15	2.26E+14	2.75E+14	2.23E+14
Non-Renewable Exergy	1.30E+15	1.35E+15	1.30E+15	2.64E+14	3.13E+14	2.61E+14
Emergy	9.82E+19	1.02E+20	9.78E+19	1.68E+19	2.04E+19	1.65E+19
Coproducts						
Non-Renewable Energy	1.50E+13	2.10E+14	4.18E+14	1.47E+13	2.09E+14	4.18E+14
Non-Renewable Exergy	1.55E+13	2.38E+14	4.35E+14	1.51E+13	2.46E+14	4.35E+14
Emergy	3.52E+16	1.39E+19	2.99E+19	3.44E+16	1.44E+19	2.99E+19

8.3. Energy and exergy content of microalgal biofuels

Szargut 2005 [25] derived an empirical relationship between the specific exergy of a liquid technical fuel, its lower heating value, and its C,H,O, S composition provided in eqn (1)

(1) $$\beta = 1.041 + 0.1728\frac{z_{H_2}}{z_C} + 0.0432\frac{z_{O_2}}{z_C} + 0.2169\frac{z_s}{z_C}\left(1 - 2.0628\frac{z_{H_2}}{z_C}\right)$$

Where Z_x is the mass fraction of the *Xth* element in the liquid technical fuel. The exergy of the liquid technical fuel is given by eqn (2)

(2) $$Exergy_{fuel} = LHV * \beta$$

The lower heating value for renewable diesel II and biodiesel was taken from GREET[19] and is provided in **Table S17.**

Table S17 - Fuel properties of Renewable Diesel and Biodiesel

Transportation Fuel	**% C**	**% H**	**% O**	**% S**	**LHV (MJ/kg-fuel)**	$\boldsymbol{\beta}$	**Exergy (MJ/kg-fuel)**
Renewable Diesel	87.1	12.9	0	0	43.97	1.066	46.90
Biodiesel	76.2	12.6	11.2	0	37.52	1.076	40.37

9. Thermodynamic return on investment for microalgal renewable diesel production pathways

Total energy, ICEC, and ECEC consumption is obtained via combining the results from EcoLCA (**Table S8**) with process level data (**Table S9** and **Table S16).** Equations for energy, exergy, and emergy return on investment are provided in the main paper. It is important to note that only processing and co-product flows are considered in the determination of return on investment, feedstock energy in not included (i.e. for microalgal biofuels direct sunlight is not included).

Table S18 – Calculation of thermodynamic return on investment for microalgal renewable diesel production based on energy, ICEC, and ECEC.

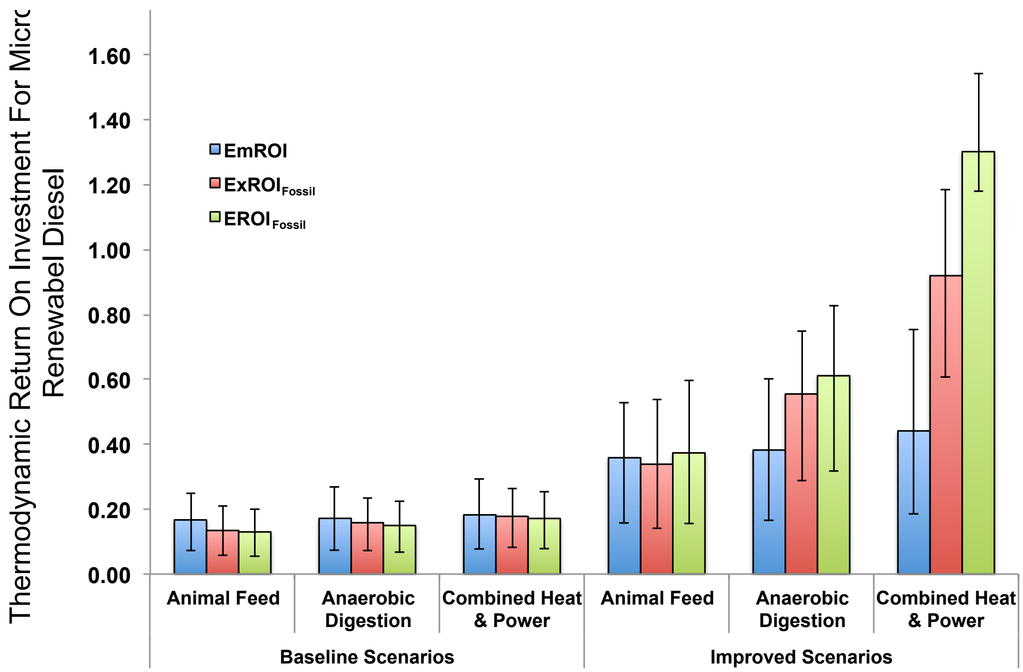
Parameters	**Microalgal RD - Baseline Scenarios**			**Microalgal RD - Improved Scenarios**		
Coproduct Scenarios	AF	AD	CHP	AF	AD	CHP
Inputs = (EcoLCA + Use Phase + Direct EGS*)						
Non-Renewable Energy	1.95E+15	1.96E+15	1.95E+15	7.45E+14	7.52E+14	7.42E+14
Non-Renewable ICEC	2.02E+15	2.02E+15	2.01E+15	8.64E+14	8.68E+14	8.61E+14
ECEC	1.96E+20	1.92E+20	1.95E+20	1.04E+20	1.00E+20	1.04E+20
Coproducts = (EcoLCA + Use Phase)						
Non-Renewable Energy	1.27E+14	3.75E+14	5.65E+14	1.26E+14	3.74E+14	5.64E+14
Non-Renewable ICEC	1.36E+14	4.24E+14	5.93E+14	1.36E+14	4.24E+14	5.93E+14
ECEC	2.79E+19	2.86E+19	4.19E+19	2.79E+19	2.86E+19	4.19E+19
Difference = (Inputs-Coproducts)						
Non-Renewable Energy	1.82E+15	1.58E+15	1.38E+15	6.19E+14	3.78E+14	1.78E+14
Non-Renewable ICEC	1.88E+15	1.59E+15	1.42E+15	7.28E+14	4.44E+14	2.68E+14
ECEC	1.68E+20	1.63E+20	1.54E+20	7.63E+19	7.16E+19	6.20E+19
Renewable Diesel						
Energy	2.36E+14	2.36E+14	2.36E+14	2.31E+14	2.31E+14	2.31E+14
Exergy	2.52E+14	2.52E+14	2.52E+14	2.47E+14	2.47E+14	2.47E+14
Exergy x τ_{max}	2.80E+19	2.80E+19	2.80E+19	2.74E+19	2.74E+19	2.74E+19
Return on Investment = (Renewable Diesel / Difference)						
EROI	0.13	0.15	0.17	0.37	0.61	1.30
ExROI	0.13	0.16	0.18	0.34	0.55	0.92
EmROI[1]	0.17	0.17	0.18	0.36	0.38	0.44

[1]EmROI = $\frac{Exergy_{RD}\ x\ \tau_{max}}{Inputs\ ECEC - Coproduct\ ECEC}$, where $\boldsymbol{\tau_{max}}$ is the transformity of petroleum diesel ~ 1.11×10^5 sej/j.

*The feedstock energy (i.e. direct sunlight) is not considered in the analysis of ROI.

The results of the analysis for microalgal renewable diesel are graphically represented via **Figure S1**

Figure S1 - Thermodynamic Return on Investment (ROI) for the examined microalgal renewable diesel production pathways and coproduct scenarios



10. ECEC sustainability and performance metrics for microalgal renewable diesel

Several ECEC-based metrics including yield ratio, Environmental Loading Ratio, Yield-to-Load Ratio, and Renewability (%) were used for quantifying the sustainability and performance of microalgae biofuel production. Detailed descriptions and definitions of these metrics are provided in Table 1 in the main paper. Traditional emergy analysis forbids allocation amongst coproducts [3]. Thus, for ECEC based performance and sustainability metrics, allocation/co-product credits were not considered. A summary table of the ECEC sustainability/performance metrics for microaglal RD are provided in **Table S19.**

Table S19 - ECEC sustainability and performance metrics for Microaglal Renewable Diesel

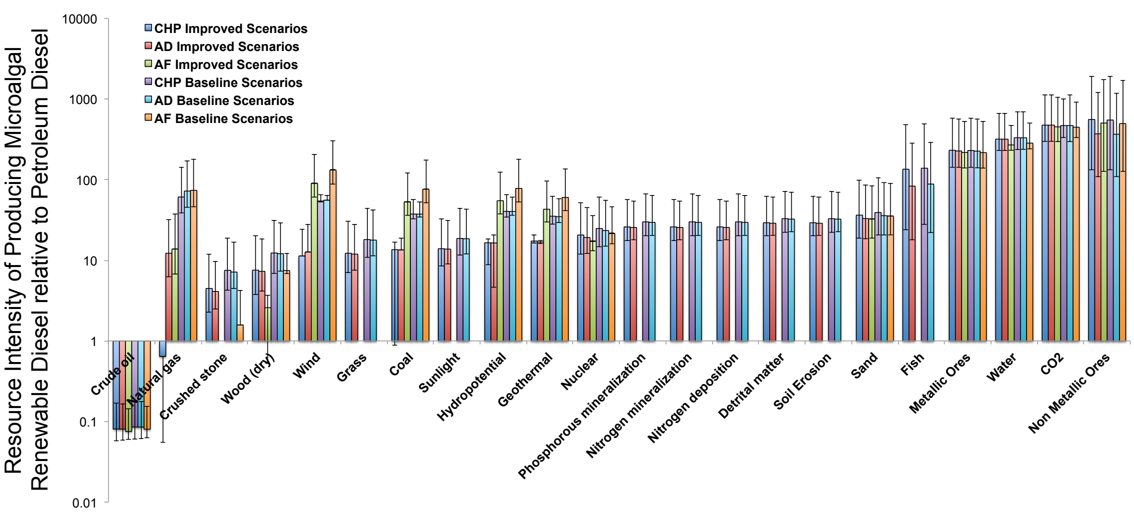
Parameters	**Microalgal RD - Baseline Scenarios**			**Microalgal RD - Improved Scenarios**		
Coproduct Scenarios	AF	AD	CHP	AF	AD	CHP
Total ECEC = (EcoLCA+Use Phase +Direct EGS)	1.96E+20	1.92E+20	1.95E+20	1.04E+20	1.00E+20	1.04E+20
Direct EGS ECEC = (ECEC solar insolation+ECEC Water +ECEC photosynthetic CO_2)	3.90E+18	3.90E+18	3.90E+18	3.88E+18	3.88E+18	3.88E+18
Non-Renewable ECEC	1.89E+20	1.85E+20	1.88E+20	9.77E+19	9.40E+19	9.73E+19
Renewable ECEC	7.09E+18	6.72E+18	7.09E+18	6.61E+18	6.24E+18	6.61E+18
ECEC Performance Metrics						

Yield Ratio[1]	1.02	1.02	1.02	1.04	1.04	1.04
Environmental Loading Ratio[2]	26.62	27.53	26.57	14.78	15.06	14.72
Yield-to-Load Ratio[3]	0.04	0.04	0.04	0.07	0.07	0.07
Renewability (%)[4]	3.62	3.51	3.63	6.34	6.23	6.36

[1]ECEC Yield Ratio is calculated as EYR = (Total ECEC / Indirect ECEC). Additionally, Indirect ECEC = (Total ECEC-Direct ECEC)
[2]Environmental Loading Ratio is calculated as ELR = (Non Ren ECEC / (Ren ECEC))
[3]Yield to Loading Ratio is calculated as YLR = (EYR / ELR)
[4]Renewablity Index % = (Ren ECEC / (Total ECEC)) x 100

Ecological resource intensity plots for baseline and improved microaglal RD fuel pathways are provided in **Figure S2.**

Figure S2 - Ecological resource intensity of producing microalgal RD relative to petroleum diesel. Resource intensity ratios were developed via taking the ratio of ECEC of resources required to produce one mega-joule (MJ) of RD to the ECEC required to produce one MJ of PD. Coproduct(s) were accounted for via system boundary expansion, i.e. ECEC from coproduct(s) were subtracted from total resource use. Some columns are not shown on the logarithmic graph due to negative value(s) that occur as a result of displacement.



11. Process level inventory for petroleum diesel

Process inventory for petroleum diesel was taken from Baral et al 2009 [3] and is provided in **Table S20**

Table S20 - Process Inventory for Petroleum Diesel

Inputs from the economy	Units	Value	1997 $	Inflation Ratio	2002 $
Crude Oil Transport	gal	2.08E+07	2.33E+05	1.12	2.61E+05
Diesel Production	**Units**	**Value**	**1997 $**	**Inflation Ratio**	**2002 $**
Crude Oil	gal	2.08E+07	1.02E+07	1.12	1.14E+07
LPG	gal	1.56E+04	5.78E+03	1.12	6.47E+03
Natural Gas	SCF	6.09E+07	2.18E+05	1.12	2.44E+05
Residual Fuel Oil	gal	8.26E+03	3.30E+03	1.12	3.70E+03
Still Gas	gal	8.92E+05	2.43E+05	1.12	2.72E+05
Petroleum Coke	gal	3.36E+05	4.19E+04	1.12	4.69E+04
Diesel	gal	2.83E+03	1.61E+03	1.12	1.80E+03
Coal	kg	2.70E+05	5.83E+03	1.12	6.53E+03
Electricity	kWh	3.26E+06	1.48E+05	1.12	1.66E+05
Steel in Refinery	kg	1.04E+04	7.40E+03	1.12	8.29E+03
Electricity (wastewater treatment)	kWh	1.92E+05	8.71E+03	1.12	9.76E+03
Rail Transportation for coal	kg	2.70E+05	2.97E+03	1.12	3.33E+03
Pipeline transportation of diesel	gal	4.00E+06	7.36E+04	1.12	8.24E+04
Outputs	**Units**	**Value**	**1997 $**	**Inflation Ratio**	**2002 $**
Diesel	gal	4.00E+06	N/A	N/A	N/A

12. Economic inputs for petroleum diesel production

Aggregating the results from **Table S20**, the economic activity for industrial sectors used in petroleum diesel is provided in **Table S21.**

Table S21 - Economic Activity ($2002) for industrial sectors used in petroleum diesel production

Sector Name	Sector Code	Economic Activity (2002 $)
Pipeline Transportation	486000	3.43E+05
Oil and Gas Extraction	211000	1.14E+07
Petroleum Refineries	324110	3.31E+05
Natural gas distribution	221200	2.51E+05
Electric Power and Generation	221100	1.76E+05
Iron and Steel Mill	331110	8.29E+03
Rail Transportation	482000	3.33E+03

13. EcoLCA, use phase, and direct EGS for petroleum diesel production

Table S22 - Direct Ecological Goods and Services as well as process fuel/energy consumption in petroleum diesel production

Direct Ecological Goods and Services	Units	Value	Energy (J)	Exergy (J)	Emergy (sej)
Crude Oil	gal	2.08E+07	2.84E+15	3.08E+15	2.79E+20
Inputs from the economy	**Units**	**Value**	**Energy (J)**	**Exergy (J)**	**Emergy (sej)**
LPG	gal	1.56E+04	1.51E+12	1.56E+12	1.73E+17
Natural Gas	SCF	6.09E+07	6.31E+13	5.80E+13	4.68E+18
Residual Fuel Oil	gal	8.26E+03	1.22E+12	1.31E+12	1.45E+17
Still Gas	gal	8.92E+05	1.21E+14	1.34E+14	1.49E+19
Petroleum Coke	gal	3.36E+05	4.84E+13	5.08E+13	5.64E+18
Diesel	gal	2.83E+03	3.90E+11	4.00E+11	4.44E+16
Coal	kg	2.70E+05	5.56E+12	7.83E+12	5.26E+17
Electricity	kWh	3.26E+06	2.85E+13	3.25E+13	1.94E+18
Electricity (wastewater treatment)	kWh	1.92E+05	1.68E+12	1.91E+12	1.14E+17
Outputs	**Units**	**Value**	**Energy (J)**	**Exergy (J)**	**Emergy (sej)**
Diesel	gal	4.00E+06	5.51E+08	5.65E+08	6.27E+19

Table S23 - Results from EcoLCA and process analysis for the production of 4.0 x 10^6 gallons of petroleum diesel

Parameters	Use Phase + Direct EGS*	EcoLCA Results
Non renewable Energy	2.70E+14	1.98E+14
Non renewable Exergy	2.87E+14	2.10E+14
Emergy	2.82E+19	2.40E+19

*Does not consider feedstock energy, (i.e. the energy, exergy, or emergy of crude oil).

14. Thermodynamic return on investment and ECEC based performance metrics for petroleum diesel

Table S24 - Thermodynamic Return on Investment and ECEC based performance metrics for Petroleum Diesel production

Thermodynamics Return On investment metrics for Petroleum Diesel			
Parameters	NR Energy	NR Exergy	Emergy
EcoLCA	1.98E+14	2.10E+14	2.40E+19
Use Phase	2.70E+14	2.87E+14	2.82E+19
Total = EcoLCA+Use Phase+Direct EGS[1]	4.68E+14	4.98E+14	5.22E+19
Market Allocation[2]	9.93E+13	1.06E+14	1.11E+19
Mass Allocation[3]	8.94E+13	9.51E+13	9.97E+18
Output - Petroleum Diesel	5.51E+14	5.65E+14	6.27E+19
Thermodynamic Return On Investment (mass)	6.16	5.94	6.29
Thermodynamic Return On Investment (market)	5.55	5.35	5.66

Thermodynamic Return On Investment (avg.)	5.86	5.65	5.98
ECEC performance and sustainability metrics for Petroleum Diesel			
Total ECEC = (EcoLCA+Use Phase+Direct EGS)[2]	3.31E+20		
Direct EGS = ECEC crude oil	2.79E+20		
Non-Renewable ECEC	3.31E+20		
Renewable ECEC	4.35E+17		
ECEC Yield Ratio (EYR)	6.34		
Environmental Loading Ratio (ELR)	760.19		
Yield to Load Ratio (YLR)	0.01		
Renewability Index (%)	0.13		

[1]The feedstock energy (i.e. crude oil) is not considered in the analysis of ROI.
[2]The feedstock energy (crude oil) is considered in evaluation of ECEC performance indicators.
[2]In market allocation 21.1% of total environmental impacts are allocated to petroleum diesel
[3]In mass allocation 19.1% of total environmental impacts are allocated to petroleum diesel

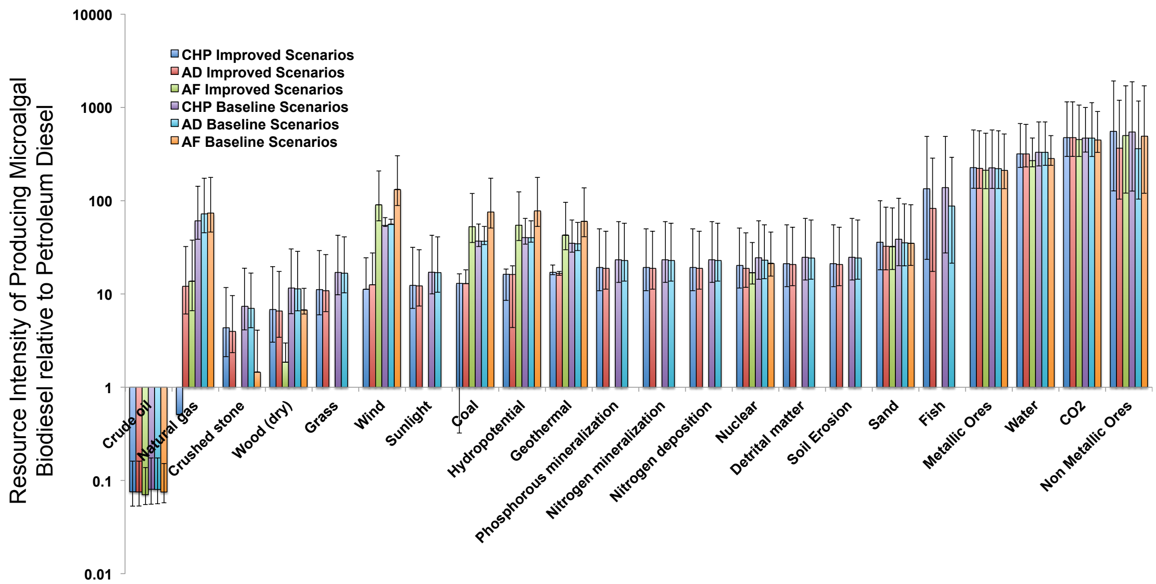
15. Thermodynamic return on investment, ECEC based performance metrics, and ecological resource intensity for microalgal biodiesel production

Analysis was conducted to determine the thermynamic ROI and ECEC performance metrics for microalgal derived biodiesel (BD). The results of the analysis are provided in **Table S25**. Additional results showing the ecological resource intensity of microalgal biodiesel production (relative to petroleum diesel) is provided in **Figure S3.**

Table S25 - Thermodynamic Return on Investment and ECEC based performance metrics for microalgal biodiesel production

	Microalgal BD - Baseline Scenarios			**Microalgal BD - Improved Scenarios**		
Coproduct Scenarios	AF	AD	CHP	AF	AD	CHP
$EROI_{fossil}$	0.13	0.17	0.17	0.37	0.61	1.28
$ExROI_{fossil}$	0.14	0.16	0.18	0.34	0.56	0.93
EmROI	0.18	0.15	0.18	0.37	0.40	0.46
Coproduct Scenarios	AF	AD	CHP	AF	AD	CHP
Renewability (%)	3.86	3.45	3.57	6.29	6.18	6.31
EYR	1.02	1.02	1.02	1.04	1.04	1.04
ELR	26.18	27.96	26.99	14.90	15.19	14.84
YLR	0.04	0.04	0.04	0.07	0.07	0.07

Figure S3 - Ecological resource intensity of producing microalgal biodiesel (BD) relative to petroleum diesel. Resource intensity ratios were developed via taking the ratio of ECEC of resources required to produce one MJ of BD to the ECEC required to produce one MJ of PD. Coproduct(s) were accounted for via system boundary expansion, i.e. ECEC from coproduct(s) were subtracted from total resource use. Some columns are not shown on the logarithmic graph due to negative value(s) that occur as a result of displacement.



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