Supporting Information

Life cycle energy and greenhouse gas analysis for algae-derived biodiesel

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Table S1 Algae strain parameters and annual dry biomass productivities

Algae Strain	Chlorella Vulgaris	Data source	Biomass productivity	Value	Unit
Mean value carbon	53%	ref.[1]	Algae concentration in water	0.5	(kg/m^3)
Mean value phosphorous	2%	ref.[1]	Wet biomass production per day	24.75	(kg/d)
Mean value nitrogen	8%	ref.[1]	Wet biomass production per area	32.97	(kg/ha)
Mean value hydrogen	8%	ref.[1]	Annual wet biomass productivity	90.34	(tons/ha/y)
Mean value oxygen	31%	ref.[1]	Dry biomass production per day	20.55	(kg/d)
Protein	282(g*kg^{-1})	ref.[2]	Dry biomass production per area	27.38	(kg/ha)
Lipid	175(g*kg^{-1})	ref.[2]	Annual dry biomass productivity	75.00	(tons/ha/y)
Carbon content	0.48(g*g^{-1})	ref.[2]	Annual dry biomass productivity (90% solid content)	67.50	(tons/ha/y)
Oil content (LHV)	0.18(g*g^{-1})	ref.[2]			
Oil density	0.981(t/m^3)	ref.[3]			

Table S2 Data used for the microalgae cultivation stage

Agro-nutrients	Application rate	Embedded energy	Embedded GHG gCO$_2$/t	Data source
NH_3	6.0(t/ha)	57.0(GJ/t)	2.309,126	ref.[1, 4, 5]
TSP	1.5(t/ha)	4.1(GJ/t)	888,410	ref.[1, 4]
K2O	0.001(kg/kg)	6.8(GJ/t)	591.880	ref.[5]

- To facilitate the synthesis of algae biomass and their productivity levels, nutrients such as nitrogen in the form of ammonia (NH3) and phosphorus in the form of superphosphate (P2O5) have to be adequately supplied according to the algae cultures' stoichiometric requirements.
- Based on the estimated elemental composition of the microalgal cells, the mass requirements for N and P in t/ha can be obtained by multiplying the dry algae biomass productivity of 75.0 t/h/y with the mean values for elemental nitrogen (8.0%) and phosphous (2.0%) contents 6, 7.
- The fossil energy utilized for ammonia production has frequently been reported at 57 GJ/t which also accounts for other downstream energy costs such as granulation, natural gas recovery, product packaging, and transportation 8, 9. The fossil energy consumption for superphosphate fertilizer production has been estimated at 4.1 GJ/t for average European production plants 8, 9.
- Moreover, flue gases with a carbon dioxide content of 12.5 vol-% (the maximum value for a natural gas-fired power station 10) from an adjacent power-plant have been assumed as a direct source of CO2 2, 11. The carbon dioxide source is pressurized and injected along the pond through PVC pipes which has been calculated to require 0.043 MJ/kg of dry algae.

Table S3 Pond and Harvesting Machinery

Pond Machinery	Material	Unit kg	Embedded energy MJ/kg	Embedded GHG kgCO$_2$/kg	Data source
Foundations	Concrete	4500	0.95	0.13	ref.[2, 12]
Pipes	PVC	687	67.5	2.50	ref.[2, 12]
Paddlewheel	Steel	50	24.4	1.77	ref.[2, 12]
	Glass fibre	256	28.0	1.53	ref.[2, 12]
Pump	Steel	20	24.4	1.77	ref.[2, 12]

Harvesting Machinery	Material	Unit kg	Embedded energy MJ/kg	Embedded GHG kgCO$_2$/kg	Data source
Concrete	Concrete	344000	0.95	0.13	ref.[2, 12]
Rotary Press	Steel	2100	24.4	1.77	ref.[2, 12]
Dryer	Steel	4000	24.4	1.77	ref.[2, 12]

- The main materials used for the building of the pond and harvesting facility include concrete blocks, PVC, glass reinforced plastics and steel [2, 13]. The pond design is consistent with industrial standards [2, 13] around a benchmark of 10 m wide, 100 m long, and 30 cm deep oval-shaped built in concrete blocks, on a 10-cm-thick sole. A PVC liner covers the concrete to decrease roughness and to avoid biomass attachment. For both the open raceway pond and the harvesting facility an average size of 0.1 ha and a lifetime of 30 years has been assumed.

Table S4 Energy and Heat requirements

	Value	Unit	Data source
CO_2 injection	0.04	MJ/kg dry	ref.[2]
Paddlewheel electricity	0.87	MJ/kg dry	ref.[2]
Pumping to settler electricity	1.23	MJ/kg dry	ref.[2]
Dryer- heat	13.80	MJ/kg dry	ref.[2]
Dryer-electricity	1.44	MJ/kg dry	ref.[2]
Press-electricity	0.23	MJ/kg dry	ref.[2]
Oil extraction-electricity[a]	0.25	MJ/kg dry	ref.[2]
Oil extraction-heat[a]	1.19	MJ/kg dry	ref.[2]
Transesterification-electricity	0.15	MJ/kg dry	ref.[2]
Transesterification-heat	0.90	MJ/kg dry	ref.[2]

[a] Heat and Electricity values are calculated for 90% dry algae biomass content

Table S5 Data used for oil extraction and transesterification chemicals

	Value	Unit	Embedded GHG gCO_2/kg biodiesel	Data source
N-Hexane	0.48	MJ/kg dry	n/a	ref.[4]
Methanol	1.86	MJ/kg oil	35.9	ref.[4, 14]
Sodium Hydroxide	0.61	MJ/kg oil	2.1	ref.[4, 14]
Sodium methoxide	0.02	MJ/kg oil	23.2	ref.[4, 14]
Hydrochlorid Acid	0.07	MJ/kg oil	7.6	ref.[4, 14]

- The algal paste yielded by flocculation has to be further dried to reach a solid 90% biomass content and be processed in oil mill facilities, typically those used for vege-table oil extraction[2]. The heat and electricity requirements of the drying process are 13.8 MJ/kg dry matter and 1.4 MJ/kg dry matter, respectively [2] and clearly induce a heavy impact on the final energetic balance and carbon footprint (see Table 4). Following the flocculation and drying step, typically 75.0 t/h/y of dry algae biomass are obtained, a value in line with literature estimates found of 90.3 t/h/y [2], 75.0 t/h/y [15] and 40.0 t/h/y [16].
- This study has focussed on dry extraction method due to data avilability and industrial penetration for biodiesel production, e.g. soybean-based biodiesel. Through the counter-current circulation of a hexane solution with an application rate of 0.48 MJ/kg [4], the algae oil is extracted from the dry biomass. The 30% algae oil content and the remaining 70% of algae cake result in the production of 22.5 t/h/y of algae oil and 52.5 t/h/y of dry algal residue[15].

Table S6 Transportation

	Value	Unit
Distance for agro-input	50.0	km
Transport service agro-input	2270.8	t-km/ha
Distance algae to biorefinery	50.0	km
Transport service algae	450.0	t-km/ha
Diesel truck efficiency	0.02	l/t-km
Diesel lower heating value	37.8	MJ/l
Mean Diesel lifecycle GHG emissions	86.0	gCO_2eq/MJ

Appendix S1 Co-product utilization

- Glycerol, seen as end-product in our study, is usually refined and sold to the pharmaceutical industry or as livestock feed. Our LCA model focuses solely on the calculation of energy credits from the reuse of the algae-derived oilcake which accounts for 70% (52.5 tons/ha/y) of dry biomass after extracting the 30% share of algae oil for further biodiesel processing. The co-product utilization options which have been considered for the reduction of the carbon cycle's electricity and heat requirements are:
- **Combined heat and power (CHP) plant.** Based on the biomass CHP demonstration plant in Guessing, Austria[17], the installation operates on a thermal efficiency of 56.3% and an electrical efficiency of 25% [17]. Through the combustion of the residual oilcake, 541 GJ/ha/y of heat and 240 GJ/ha/y of electricity are generated from the biomass CHP unit. However, regardless of the higher efficiency level of the CHP unit the microalgae-to-biodiesel plant's electricity and heat inputs cannot be completely satisfied and in each case additional capacity must be purchased from the local grid, see Table 7.

- **Direct Combustion.** With an assumed 85% efficiency level, only 817 GJ/t/ha of end use heat can be generated [18]. This partially offsets the total heat requirements of 1,136 GJ/ha/y in the process and requires the further purchase of heat from the national grid, see Table 7.
- **Co-firing coal power plant.** The option simulates the operation at an existing coal-fired power plant with a cofiring ratio of 10% biomass [19]. A plant efficiency of 33% has been esti-mated which is slightly below those of baseline power plants without cofiring [19, 20]. The combustion of the oilcake as part of a coal-fired power station results in the production of 317 GJ/ha/y of end use electricity. In the country scenarios, the end use electricity volume is large enough to satisfy all the electricity requirements of the fuel cycle and result in a surplus which is used to displace electricity from the grid, (indicated in Table 7 by negative values).

Table S7 : Supplementary grid primary energy supply required by co-product utilization options[a]

	CHP system[b]		Direct Combustion[c]	Co-firing coal power plant[d]
	Heat	Electricity	Heat	Electricity
China	738.0	167.9	395.8	-31.1
UK	673.5	114.0	361.2	-21.1
France	590.7	15.7	316.8	-2.9
Brazil	660.1	16.0	354.0	-3.0
Nigeria	660.8	113.3	354.4	-24.7
Saudi Arabia	660.8	182.4	354.4	-33.8

[a]Values show complementary grid energy supply or displaceable surplus (highlighted by negative values), related to amount of final energy generated by each co-product utilization method.
[b]541 GJ/ha/y end heat and 240 GJ/ha/y end electricity generated in biomass CHP plant.
[c]817 GJ/ha/y end heat generated in biomass heating system.
[d]317 GJ/ha/y end electricity generated in co-fired coal power plant.

Appendix S2 Country-specific LCA studies

Table S8 Energy and carbon intensity of national heat grid[21]

	Final Heat Demand	Primary Fossil Energy	Primary Fossil Energy/Final Heat[a]	Carbon Intensity/ Heat[b]
Unit	**PJ**	**PJ**	**PJ/PJ**	**gCO_{2eq}/MJ**
China	2586.0	3209.3	1.24	130.4
UK	49.8	49.8	1.13	83.4
France	160.8	159.7	0.99	74.9
Brazil[c]	15.7	-	1.11	84.1
Nigeria	-	-	1.11	79.1
Saudi Arabia[c]	-	-	1.11	81.6

[a] Primary Energy consumption/MJ heat is based in Brazil, Nigeria and Saudi Arabia on the energy intensity of a natural gas powered grid
[b] Carbon Intensity per primary fuel burned for the production of heat is sourced from ref [5]
[c] The calculations for the carbon intensity/ MJ of heat produced in Saudi Arabia and Brazil are based on the nations' consumption figures and availability of fossil fuel sources

Table S9 Energy and carbon intensity of national electricity grid[21, 22]

	Final Electricity Demand	Primary Fossil Energy	Primary Fossil Energy/Final Electricity[a]	Carbon Intensity/ Electricity[b]
Unit	**TWh**	**TWh**	**MJ/MJ**	**gCO_{2eq}/MJ**
China	279.3	8490.1	2.59	275.6
UK	396.1	696.5	1.76	155.7
France	569.8	137.9	0.24	24.7
Brazil	445.1	109.8	0.25	24.4
Nigeria	22.9	47.3	2.06	13.0
Saudi Arabia	189.1	531.9	2.81	222.5

[a] Country specific grid efficiency data: ref [22].
[b] Carbon intensity data per MJ of primary energy consumed: ref[23 5].

Appendix S3 Algal fuel's requirement of Global Land Area

Global fossil derived diesel consumption	1,126 billion tons ref.[40]
Total algae-derived biodiesel production	850,500 MJ/ha/y
Algal fuel required land mass	57,3 million ha/y

Supporting References for Tables S1–S9 and Appendix S1-S3.

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