LIFE CYCLE ASSESSMENT OF THE PRODUCTION CHAIN OF OIL-RICH BIOMASS TO GENERATE BTL AVIATION FUEL DERIVED FROM MICRAOALGAE

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Considerable efforts are made to generate drop-in aviation fuels from microalgae to avoid competition with food production. Synthetic biofuel from oil-rich biomass is produced along four process lines: cultivation, harvest, extraction of raw material and conversion to fuel. This study deals with the life cycle assessment of fuel obtained from cultivation of the fresh water alga *Auxenochlorella protothecoides* and concentrates on the cultivation in open ponds as well as the harvesting steps preconcentration, electroporation and dewatering. Energy balance and environmental impact is analysed using GaBi software and data base. The main goal is to identify those factors or processes exerting the strongest impact, either environmentally or from the point of view of the energy balance. Production of one kilogram of dry oil-rich algal biomass (kg DM) consumes 118.56 MJ of primary energy. The primary energy demand is apportioned as follows: 71.7 % during proliferation in Erlenmeyer flags and bubble columns, 15.5 % by cultivation in raceway ponds and 12.8 % in preconcentration, electroporation and dewatering. This converts into a net energy ratio (*NER*) of 0.266 and a CO_2-equivalent of 6.45 kg CO_2 per kg DM. These values are disadvantageous when compared to kerosene (*NER* = 0.867, 0.384 kg CO_2 per kg kerosene). Production can be optimized using process energy from regenerative sources such as hydroelectric power (*NER* = 0.545, 1.27 CO_2 per kg DM). In this case total primary energy input must be corrected for the portion of renewable sources resulting in a NER_{corr} of 3.04. CO_2-equivalents per kg DM remain unfavourably high as compared to kerosene; the main driver responsible for this discrepancy is the usage of freshwater and fertilizer.

Biofuel, microalgae, auxenochlorella protothecoides, energy balance, electroporation, renewable energy.

NOMENCLATURE

BtL	Biomass-to-liquid
CtL	Coal-to-liquid
C_B	Total suspended solids
CO_2	Carbon dioxide
GtL	Gas-to-liquid
Hu	Calorific value
HVO	Hydrogenated vegetable oil
corr	corrected
NER	Net energy ration
DM	Dry matter
N	Nitrogen
P	Phosphorous

1 INTRODUCTION

Biofuels currently are mostly produced from terrestrial plants containing oil, starch or sugar such as soy beans, raps, corn and sunflower seeds or palm oil. Present technologies are almost fully developed but cultivation involves substantial land use and needs fertile soils 5. Hence, considerable efforts are made to generate biofuels (including biodiesel) from other sources to avoid competition with food production. This is especially true for aviation fuels. Microalgae turned out to be an almost ideal alternative as they contain significantly higher concentrations of oil and carbohydrates, possess high to very high photosynthetic activity and require comparatively less land use than terrestrial plants 22. Yield from microalgae with oil concentrations about 30% per dry weight is 9 to 300 times higher than that of conventional crops 5.

From an economical point of view it is most desirable that a biofuel may be used without any alterations to the aircraft and the engines (drop-in fuels). Possible processes to produce drop-in fuels focus on Fischer-Tropsch synthesis applied to coal, gas or biomass (CtL, GtL, BtL) and hydration of vegetable oil (HVO). Raw material is converted to carbohydrates possessing almost identical chemical properties when compared to kerosene (7, 8). BtL and HVO from microalgae are considered an environmentally sensible alternative with high potential to replace fossil resources.

2 PRINCIPLES OF BIOFUEL PRODUCTION FROM MICROALGAE

Biofuel is produced along four process lines: cultivation, harvest, extraction of raw material and conversion to fuel. Cultivation is managed in open or closed systems (1, 3, 5). Open systems are simple, cost-efficient and mainly composed of concrete ponds (raceway ponds) where the alga suspension is driven by paddle wheels 1. However, such systems are susceptible to contamination and changes in the dissolved load as a result from evaporation or precipitation 1. Closed systems (photobioreactors) are complex, require intense maintenance and demand much more energy than open systems (5, 15). Both systems need carefully adjusted quantities of nutrients (N, P), CO_2 and light. Harvesting methods (centrifugation, flotation, filtration, and flocculation) depend on species composition of the alga suspension and cell sizes 1. After compaction the remaining intracellular water must be extracted by mechanical or chemical methods. In the final step lipids are converted to biodiesel or HVO and oil-rich biomass is transformed into BtL 6. Our research project concentrates on the life cycle assessment of synthetic fuel obtained from cultivation of a fresh water alga (*Auxenochlorella protothecoides*) particularly well suited for biofuel production as a result from its very high photosynthetic activity and oil content. Energy balance and environmental impact is analysed using GaBi software and data base 19. This paper presents results from the life cycle assessment of the cultivation, harvest and extraction paths of the production chain leading to oil-rich biomass.

3 LIFE CYLE ASSESSMENT

Input, output and environmental impact are quantified following the procedure defined in DIN EN ISO 14044, i.e. study goal and scope, inventory analysis, impact and interpretation 9. On this background it is possible to clearly identify those factors or processes exerting the strongest impact, either environmentally or from the point of view of the energy balance. Industrial-size plants for the production of biofuel from microalgae do not exist until today but a wealth of data is already available from laboratory and pilot plants (2, 4).

Within the scope of this study the following assumptions and parameters are made and set:

- the functional unit of life cycle assessment is 1 kg dry matter (kg DM)
- biomass production and extraction is performed in Europe
- evaporation totals 10 l m^{-2} d and thus does not require fertilizer compensation or dilution 1
- 1 kg DM fixes 1.8 kg CO_2 (5, 21)
- concentration of suspended organic solids (C_B) is constant throughout the cultivation process (C_B = 1.3 g/l)
- residual water from the harvesting step(s) can be recycled without further treatment; excess water enters the waste water balance
- the calorific value (H_u) of 1 kg DM is 31.55 MJ 16
- stepwise cultivation following the initial laboratory stage produces less contamination than continuous cultivation 3
- facilities and in particular cost and environmental impact related to their production do not enter the life cycle assessment. This is common practice in assessments of long-lived and highly productive assets on the reason that the emissions caused by the working unit surpass those of facility manufacturing by several orders of magnitude 19.

4 INVENTORY ANALYSIS OF PRODUCTION OF OIL-RICH BIOMASS

4.1 Cultivation

Cultivation is a stepwise process chain (Fig. 1) starting with breeding under controlled laboratory conditions, proliferation in Erlenmeyer flags and further alga enrichment in bubble columns followed by raceway ponds of increasing capacity. Proliferation in Erlenmeyer flags takes 7 days. Further enrichment takes 10 days per step; lipid enrichment in the last step takes 15 days. Each cultivation unit must be inoculated with fresh alga suspension to avoid contamination with other algae or undesired organisms 4. The inoculation volume amounts to 10 - 15 % of the volume of the cultivation unit; the rest is fresh water. Preceding units must be multiplied according to the inoculation volume needed in the following unit (Fig. 1).

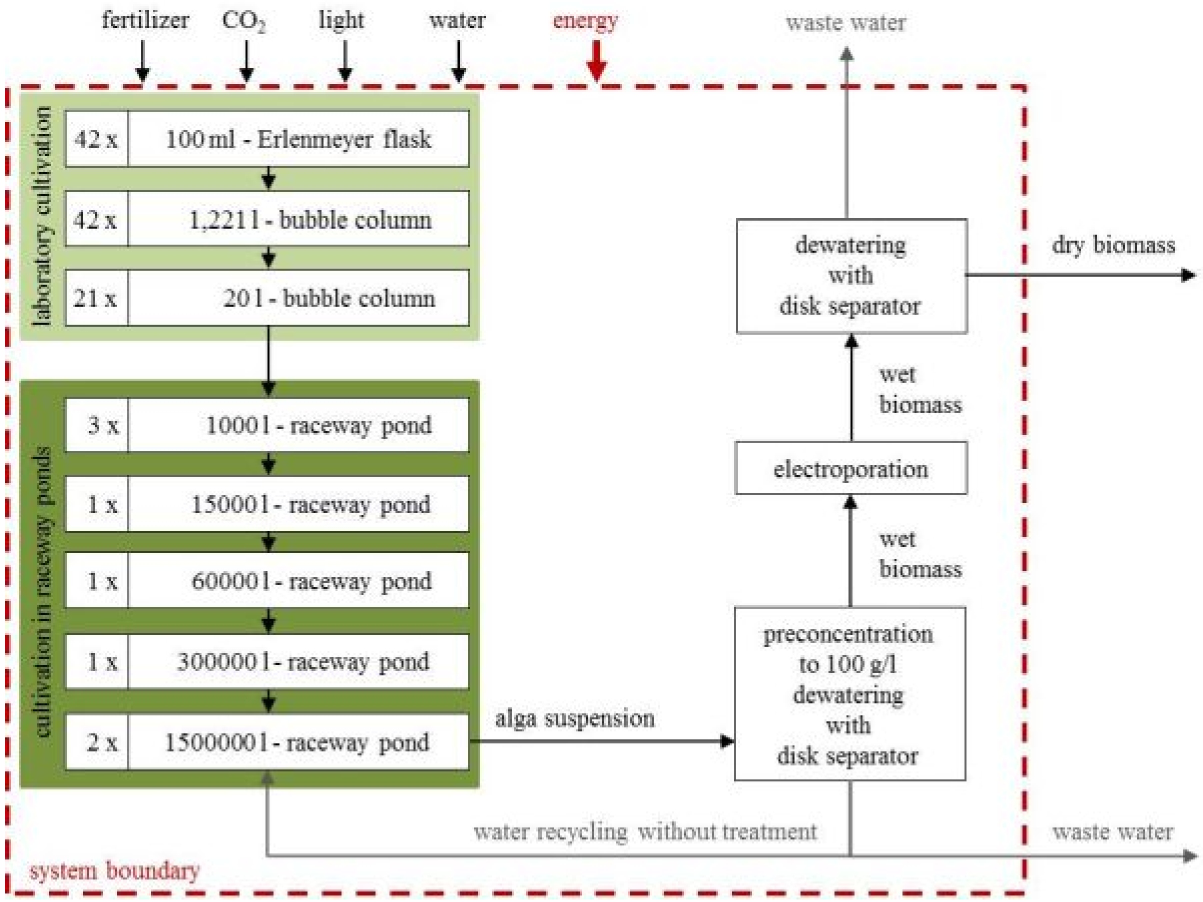

Fig. 1. Oil-rich biomass is produced along four process lines: cultivation, preconcentration, electroporation and dewatering

A typical path through the production steps requires the following quantities:

- two 1.221 l bubble columns replenish one 20 l bubble column
- seven 20 l bubble columns replenish one 1000 l raceway pond
- three 1000 l raceway pond replenish one 15000 l raceway pond
- further steps are explained in Fig. 2. The last step (lipid enrichment) occurs in a 1500000 l raceway pond. In comparison the foregoing steps it takes 15 days; thus, to obtain a harvest every 10 days two of these large ponds are needed. The final output totals 1950 kg DM per pond.

For optimal growing *Auxenochlorella protothecoides* requires accurate doses (Tab. 1) of nitrogen (N), phosphorus (P), magnesium (Mg), iron (Fe) and calcium (Ca). Biomass enrichment works best at a nitrogen concentration of 2 mmol per litre. In the last step, however, this concentration must be reduced to 1 mmol per litre because otherwise algae will not enrich lipids. Constant pH control to buffer the input of CO_2 is maintained with KH_2PO_4 (3 mmol per litre) 4.

Tab. 1. Nutrient concentration in mmol l^{-1} **4**

Nutrient	mmol l^{-1}
$(NH)_4 2HPO_4$	2.0
KH_2PO_4	3.0
$MgSO_4$*7 $H_2 0$	0.5
FeSO4*7 $H_2 0$	0.02
$CaCl_2$*2 H_2O	0.2

The proliferation step in Erlenmeyer flags needs electrical energy for illumination, cooling, aeration, the orbital shaker and cleaning totalling 66 kWh in 7 days for 200 ml alga suspension in two flags. Ensuing cultivation in two 1.221 l bubble columns consumes 377.2 kWh for illumination, air conditioning and injection of CO_2. A 20 l bubble column expends 353.4 kWh in 10 days. Illumination scales per area while cooling scales per volume ($Q \sim V^{2/3}$).

Suspension in raceway ponds is kept in circulation by paddle wheels producing a mean of 30 cm s^{-1} consuming 0.016 kWh m^{-2} d^{-1} (1, 3). In the last pond (lipid enrichment) circulation requires 0.65 kWh per kg DM whereas all previous ponds consume 0.41 kWh per kg DM. The carbonator injects 2.6 kg CO_2 per 75 m^2 surface in 10 hours 3; per kg CO_2 0.0222 kWh are needed 17. It is economically and ecologically favourable to use industrial flue gas from power plants 22. Excess CO_2 via outgassing from the water surface enters the life cycle assessment. Photosynthetic produced oxygen is regarded as an emission. Transferring suspension among raceway ponds with circular pumps yielding 50 m^3 h^{-1} consumes 9 kW 14. Energetic requirements are summarized in Tab. 2.

Tab. 2. Process energy of raceway pond in kWh per kg DM (**1**, 14, 17)

Process step	kWh per kg DM
Paddle wheel	0.41 (0.65)
CO_2-injection	0.0222
Pumping	0.138

4.2 Pretreatment

The green alga *Auxenochlorella protothecoides* measures 2 - 12 µm 13. As a result from this size distribution it is compulsory to use centrifuges to guarantee an adequate throughput and the desired concentration of C_B = 100 g l^{-1}. A special disk separator for microalgae providing a throughput of 24 m^3 h^{-1} possesses 30 kW effective capacity (11, 20).

4.3 Electroporation

A common method to accede the cell water is the destruction of membranes by electroporation under high voltage producing holes permeable for water molecules (1012). Until today only pilot plants are functional yielding a throughput of 0.5 l h^{-1} consuming 1.5 MJ per kg DM 10.

4.4 Dewatering

Final solid-liquid separation must remove interstitial and intracellular free water to separate the concentrate of oil-rich biomass using disk separators from the pretreatment step.

Tab. 3 summarizes energy inputs and operation materials for the complete production chain normalized to 1 kg DM.

Tab. 3. Energy inputs and operation materials for the complete production chain normalised to kg DM (**1**, 14, 17)

Process step	Amount per kg DM	Unity
Laboratory Cultivation		
Electric energy	8.578	kWh
Fertilizer	$2{,}1\cdot10^{-4}$	kg
Fresh water	0.228	kg
Raceway ponds		
Electric energy	0.802	kWh
Fertilizer	0.729	kg
Fresh water	2.6	kg
CO_2	564.4	kg
Preconcentration		
Electric energy	1.1	kWh
Electroporation		
Electric energy	0.417	kWh
Dewatering		
Electric energy	0.0125	kWh

5 RESULTS

Fig. 2 details the distribution of the primary energy demand among the different production steps leading to the reference mass (1 kg DM). The cumulative primary energy demand for the entire process chain is 118.56 MJ per kg DM. The primary energy demand is apportioned as follows: 71.7 % during proliferation in Erlenmeyer flags and bubble columns, 15.5 % by cultivation in raceway ponds and 12.8 % in harvesting steps (pretreatment, electroporation, dewatering). It is obvious that the high primary energy demand of the laboratory stage results from energy consuming processes such as cooling (82.8 %) and illumination (10.5 %). The primary energy demand for operation material is under 1 ‰. In a balance of the complete production chain process energy again is responsible for the bulk of primary energy demand (91.2 %). Fertilizer and freshwater account for 8.8 %.

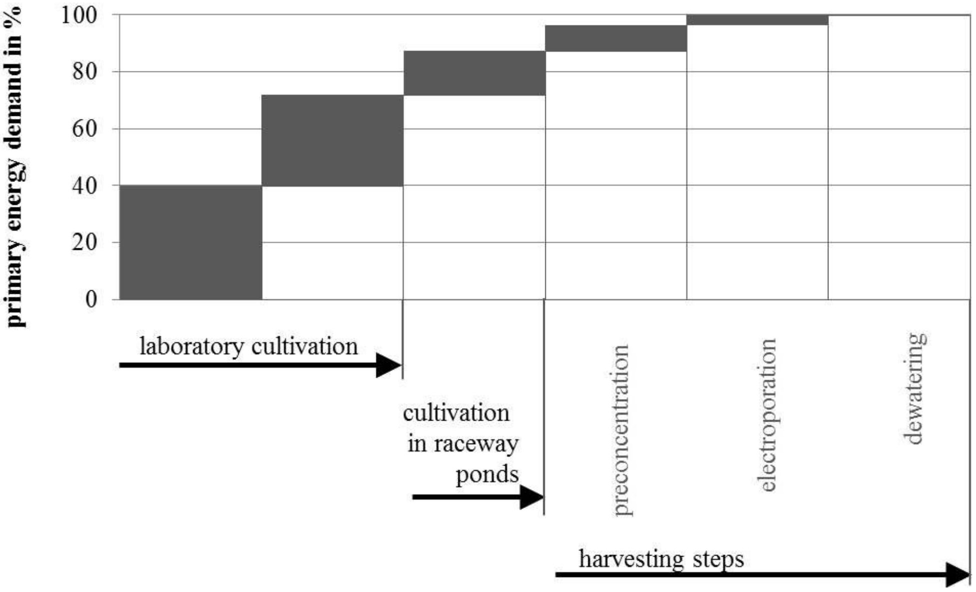

Fig. 2. Distribution of the cumulative primary energy to produce 1 kg DM

Modelling the production of the reference mass (1 kg DM) with GaBi (Fig. 3) resulted in a total primary energy demand of 118.56 MJ distributed between process energy (39.27 MJ) and operational material (10.4 MJ related to 567.957 kg). 102.8 MJ out of the sum of 118.56 MJ are from non-renewable sources and 15.76 MJ are from regenerative input. The non-renewable portion splits into process energy (90.2 %) and operational material (9.8 %). Process energy enters modelling as European energy mix requiring 2.75 MJ primary energy to create an output of 1 MJ. Out of these 2.75 MJ 2.36 MJ correspond to non-renewable and 0.39 MJ to renewable sources 19.

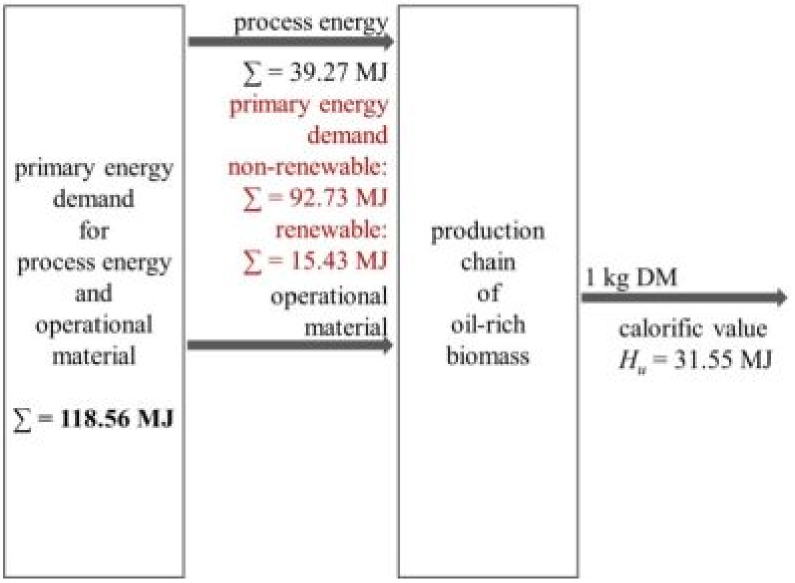

Fig. 3. Composition of the primary energy consumption to produce 1 kg DM algal biomass

Relations between the type of process energy and the corresponding portions of non-renewable/renewable sources of energy are shown in Fig. 4. Photovoltaic energy production rises the cumulative primary energy demand from 118.56 MJ to 315.6 MJ but the split into 18.98 MJ non-renewable and 296.66 MJ renewable ultimately entails a positive balance. Wind and hydroelectric energy supply reduce primary energy demand to 110.48 MJ and 57.91 MJ, respectively. In these cases the non-renewable portion is even below 2 %.

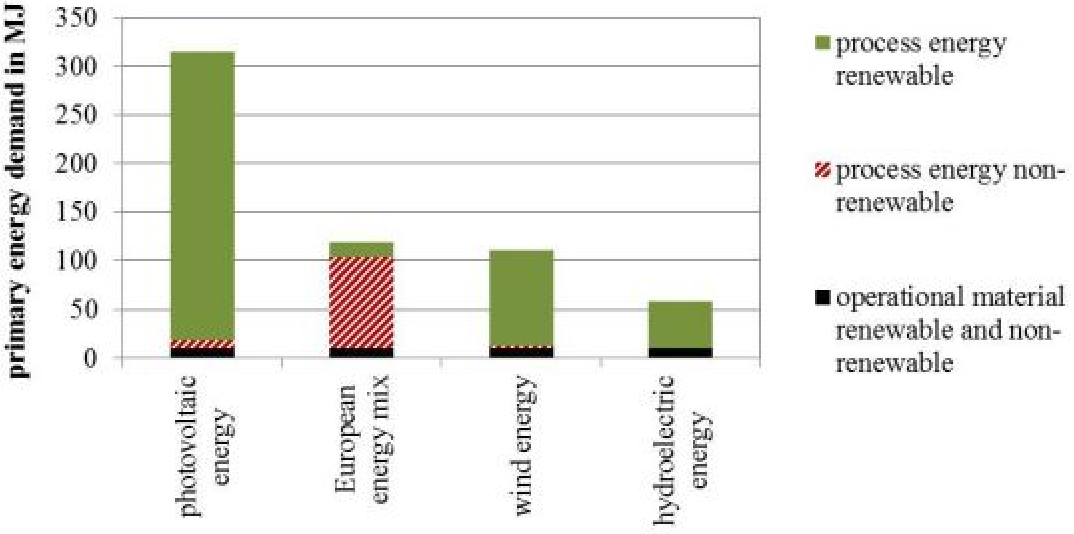

Fig. 4. Primary energy consumption in MJ per kg DM depending on different sources of electric energy

The net energy ratio (*NER*) turned out to be a useful term when largely differing products linked with different processes are to be compared. The ratio compares the calorific value (H_u) of a product with total primary energy demand involved in production 16.

$$NER = \frac{\text{calorific value}}{\text{total primary energy demand}}. \qquad (1)$$

Consequently, a process is economically reasonable when *NER* is > 1 because less energy is required for production than stored in product. For the case studied here the *NER* related to the production of 1 kg DM is 0.266 (H_u = 31.55 MJ, cumulative demand = 118.56 MJ). This is unfavourable per se and it is even more so when compared to the *NER* of kerosene (0.867) 19. Using wind energy rises the *NER* to 0.286; water energy increases *NER* to 0.545 but photovoltaic energy sources result in very low values (NER = 0.1). However, as this balance integrates both non-renewable and renewable sources of primary energy demand a correction must be applied to the renewable portion because it is supposed to be environmentally neutral and does not imply the use of fossil resources. Accordingly, NER_{corr} is calculated as the relation between H_u and the non-renewable portion of the primary energy demand 18. In Tab. 4 *NER* and NER_{corr} of the process chain leading to algal biomass production are plotted against different sources of energy and compared to kerosene.

$$NER_{corr} = \frac{\text{calorific value}}{\text{non-renewable primary energy demand}}. \qquad (2)$$

Tab. 4 - *NER* and NER_{corr} of the process chain leading to algal biomass production for different sources of electric energy and for kerosene

Sources of electric energy	*NER*	NER_{corr}
European energy mix	0.266	0.307
Photovoltaic energy	0.1	1.66
Wind energy	0.286	2.66
Hydroelectric energy	0.545	3.04
for comparison		
Kerosene	0.867	0.869

It is most remarkable that even the initial biomass production path of biofuel production from microalgae is economically only reasonable when renewable sources of energy are used. Expectedly, CO_2-equivalents also are well below the reference value of kerosene: 6.45 kg CO_2-equivalents per kg DM as compared to 0.384 kg CO_2-equivalents per kg kerosene 19. If process energy is derived from renewable sources CO_2-equivalents per kg DM reduce to 1.76 (photovoltaic), 1.33 (wind) and 1.27 (water). Even so the values are still higher than in the case of kerosene; the main driver responsible for this discrepancy is the usage of freshwater and fertilizer.

6 CONCLUSION

This study quantitatively demonstrates that production of one kilogram of algal biomass from the fresh water microalga *Auxenochlorella protothecoides* consumes 118.56 MJ of primary energy. This corresponds to 91.2 % of the total process energy; the remaining 8.8 % relate to use of fertilizers and fresh water. Employing European electrical energy mix results in a CO_2-equivalent of 6.45 kg CO_2 per kg DM and delivers a *NER* of 0.266. This value is adverse to that of kerosene (*NER* = 0.867). If process energy originates from regenerative sources the CO2 equivalent drops to 1.27 of CO_2 per kg DM and the *NER* rises to 0.545. NER_{corr} considerably improves from 0.545 to 3.04 when total primary energy input is corrected for the portion of renewable sources. Hence, it becomes clear that generation of algal biomass for synthetic biofuel production is economically and environmentally disadvantageous unless primary energy input stems from renewable sources. In particular, this implies that independently from all other processes of the production line (e.g., refining, transport) all processes and operational materials must be strictly designed to the principles of minimal release of CO_2.

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ОЦЕНКА ПРОИЗВОДСТВЕННОЙ ЦЕПОЧКИ БИОМАСС ИЗ НАСЫЩЕННЫХ ЖИРАМИ МИКРОВОДОРОСЛЕЙ ДЛЯ ПОЛУЧЕНИЯ АВИАЦИОННОГО БИОТОПЛИВА

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В настоящее время прилагаются значительные усилия для создания авиационного биотоплива из микроводорослей, абсолютно взаимозаменяемого с традиционным видами авиационных топлив. Эти действия осуществляются, чтобы не использовать для этих целей продукты питания. Синтетическое биотопливо из биомассы с высоким содержание жировых компонентов изготавливается по следующей технологической цепочке: выращивание культур, сбор урожая, извлечение сырьевой базы, переработка её в топливо. Это исследование посвящено технологическому циклу производства топлива, полученного культивированием водорослей *Auxenochlorella protothecoides* в пресной воде и сосредоточено на культивировании культуры в открытых водоёмах, а также на последовательности действий в ходе сбора сырья, таких как: предварительное обогащение, электропорация и обезвоживание. Топливно-энергетический баланс и воздействие на окружающую среду анализируется при помощи программного пакета GaBi и базы данных. Главная цель работы заключается в выявлении факторов и процессов, оказывающих наибольшее влияние как на экологическую составляющую, так и на энергетический баланс. Так для производства одного килограмма обезвоженной биомассы из водорослей с высоким содержанием жировых компонентов (кг сухого вещества) требуется затратить 118,56 МДж энергии. Потребление энергии распределяется следующим образом: 71,7% расходуется в процессе роста микроорганизмов к колбах Эрленмейера и в барботирующих ферментёрах, 15,5% используется для выращивания в каналах водоёма и 12,8% потребляется для предварительного обогащения, электропорации и обезвоживания. Преобразуя величины в соотношение суммарной энергии (NER), получили значение 0,266, а в CO_2 эквиваленте получили 6,45 кг CO_2 на кг сухого вещества. Полученные значения хуже аналогичных зависимостей для керосина (NER = 0,867; 0,384 кг CO_2 на кг керосина). Производство может быть оптимизировано благодаря использованию требуемой энергии из возобновляемых источников, таких, например, как гидроэлектростанции (NER = 0,545; 1,27 кг CO_2 на кг сухого вещества). В этом случае суммарная величина энергии на входе должна быть скорректирована при использовании возобновляемых источников, приводящих NER к 3,04. Тем не менее, оценка CO_2 эквивалента на килограмм сухого вещества остаётся по - прежнему неблагоприятно высокой в сравнении с керосином. Основной причиной столь существенного различия является использование чистой лабораторной воды и удобрений.

Биотопливо, микроводоросли, топливно-энергетический баланс, электропорация, возобновляемая энергия.

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