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LIFE CYCLE ASSESSMENT OF BTL AS COMPARED TO HVO PATHS IN ALTERNATIVE AVIATION FUEL PRODUCTION

M. Gehrer, H. Seyfried, S. Staudacher
Institute of Aircraft Propulsion Systems
University of Stuttgart
Pfaffenwaldring 6, 70569 Stuttgart, Germany

Abstract

Possible processes to produce drop-in fuels focus on Fischer-Tropsch synthesis applied to oil-rich biomass (BtL), biocoal (CtL) and hydration of vegetable oil (HVO). Biofuels from microalgae are produced along four process lines: cultivation, harvest, extraction of raw material and conversion to fuel. This study deals with the life cycle assessment of the complete (partly theoretical) production chain of synthetic fuels (BtL, CtL and HVO) obtained from cultivation of a fresh water alga (*Auxenochlorella protothecoides*). Energy balance and environmental impact are analysed using GaBi software and data base. The main goal is to identify those factors, processes or production paths exerting the strongest impact, either environmentally or from the point of view of the energy balance. Using conventional sources of electric energy there is no economic competitive to conventional kerosene ($NER = 1.2$, CO_2-equivalents per kg kerosene = 0.395 kg) among the different concepts of biofuel production from microalgae (Btl, CtL and HVO). However input from regenerative energy sources renders almost all CtL and HVO paths economic. Even under these conditions the BtL path remains energetically ineffective; its CO_2-equivalents are better than those of kerosene only if hydroelectrically generated energy is used. In almost all cases the amount of primary energy demanded by laboratory cultivation is surprisingly high. We suspect that the high demand created by this initial production step might be an artefact of scaling when parameters of laboratory, pilot plant or theoretical processes are adapted to industrial dimensions.

NOMENCLATURE

BP	By-products
BtL	Biomass-to-liquid
CtL	Coal-to-liquid
GtL	Gas-to-liquid
C_B	Total suspended solids in g l^{-1}
CO_2	Carbon dioxide
CO_2-eq	CO_2-equivalent
corr	Corrected
DM	Dry matter
FM	Fresh matter
$FeSO_4$	Ferrous sulphate
H_u	Calorific value
H_3PO_4	Phosphoric acid
HVO	Hydrogenated vegetable oil
KEA	Cumulative primary energy demand in MJ
$KNRA$	Cumulative non-renewable primary energy demand in MJ
NaOH	Sodium hydroxide
NER	Net energy ratio
P	Production
TSS	Total suspended solids in %

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 [8]. Hence, considerable efforts are made to generate biofuels 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 possess high to very high photosynthetic activity, require comparatively less land use than terrestrial plants and contain significantly higher concentrations of oil and carbohydrates [43]. Yield from microalgae with oil concentrations about 30 % per dry weight is 9 to 300 times higher than that of conventional crops [8].

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 [11, 12]. BtL, CtL and HVO from microalgae are considered an environmentally sensible alternative with high potential to replace fossil resources.

2 BIOFUEL PRODUCTION FROM MICROALGAE

Biofuel from microalgae is produced along four process steps: cultivation, harvest, extraction of raw material and conversion to fuel (Fig. 1).

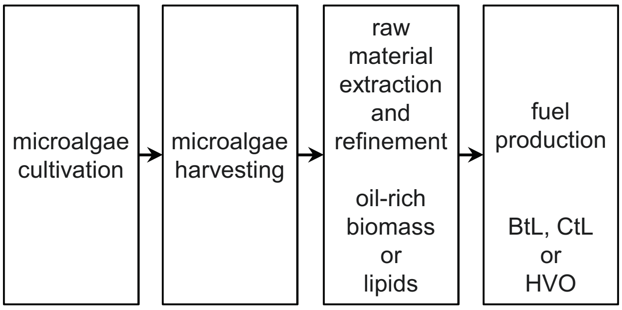

Fig. 1: Production path of biofuels based on microalgae

Cultivation is managed in open or closed systems [2, 4, 8]. Open systems are simple, cost-efficient and mainly composed of concrete ponds (raceway ponds) where the alga suspension is driven by paddle wheels [2]. However, such systems are susceptible to contamination and changes in the dissolved load as a result from evaporation or precipitation [2]. Closed systems (photobioreactors) are complex, require intense maintenance and demand much more energy than open systems [8, 27]. Both systems need carefully adjusted quantities of nutrients, CO_2 and light [43]. Harvesting methods (flotation, flocculation, filtration or centrifugation) depend on species composition of the alga suspension and cell sizes [2]. After compaction the remaining intracellular water must be extracted. Therefore the alga cell walls must be destroyed. This can be done by mechanic forces (bead mill, homogeniser or electroporation) or by chemical or biological conversion [16, 29]. Afterwards raw materials can be extracted and refined by chemical or mechanical methods (lipid extrcation by solvents, centrifugation) [37]. In the final step oil-rich biomass is transformed into BtL or transformed to biocoal and then converted to CtL; lipids are converted into biodiesel or HVO [9].

Our research project concentrates on the life cycle assessment LCA of synthetic fuels (BtL, CtL and HVO) obtained from cultivation of the fresh water alga *Auxenochlorella protothecoides* which is particularly well suited for biofuel production as a result from its very high photosynthetic activity, growth rate and oil content [5]. Energy balance and environmental impact are analysed using GaBi software and data base [35]. This paper presents results from the life cycle assessment of the complete production path(s) of the production chain leading to BtL, CtL and HVO.

3 LIFE CYCLE 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 [13]. 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 [3, 5].

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 fuel
- biomass production and extraction is performed in Europe and includes transport of raw material to the refinery (transport distance: 100 km)
- stepwise cultivation following the initial laboratory stage produces less contamination (e.g., bacteria) than continuous cultivation [4]
- evaporation totals $10\,\mathrm{l\,m^{-2}\,d}$ and thus does not require fertilizer compensation or dilution [2]
- 1 kg dry matter (kg DM) fixes 1.8 kg CO_2 [8, 42]
- concentration of suspended organic solids (C_B) is constant throughout the cultivation process (C_B= $1.3\,\mathrm{g\,DM\,l^{-1}}$)
- residual water from the harvesting step(s) can be recycled without further treatment; excess water enters the waste water balance
- energy gains obtained along a production path are credited to the total energy balance
- energy inputs and emissions are associated to the fuel and not allocated to any by-products (BP)
- 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 [30, 35]
- all materials used enter the balance even if their respective masses are below 1 % (which in common practice is the cut-off criterion [30]). At present life cycle data of some materials used in small portions such as ferrous sulphate ($FeSO_4$)

and phosphoric acid (H_3PO_4) data are not available; these materials do not enter the balance. In some processes such as lipid extraction hexane is used in larger portions. As GaBi does not provide life cycle details for hexane we take the values available for the nearest analogous compound cyclohexane

- the calorific value (H_u) varies for the different products within the production path of fuels based on microalgae (biomass, lipid, biocoal and fuel, Tab. 1).

Tab. 1: Calorific value (H_u) of products within the production paths of biofuel based on microalgae

Products	H_u in MJ kg^{-1}	reference
kg DM	21	[20]
kg biocoal	21–26	[38]
kg oil	38.3	[15]
kg BtL fuel	44.2	[7]
kg CtL fuel	42.5	[7]
kg HVO fuel	44	[24, 33]

Production of biofuel from microalgae splits into two main process lines leading to the BtL/CtL and HVO, respectively. In the present study we consider biofuel production on the basis of the fresh water alga *Auxenochlorella protothecoides*. Both process lines are partly overlapping in the initial steps of cultivation and harvesting but differ in subsequent steps of raw material extraction and fuel production (Fig. 2).

3.1 Cultivation and harvest

The cultivation and harvesting steps are described in detail in [18]. Tab. 2 summarises energy inputs and operation materials normalized to 1 kg DM for the complete chain of cultivation and harvesting steps. Cultivation is a stepwise staggered process chain 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 [18]. For optimal growing *Auxenochlorella protothecoides* requires accurate doses of nitrogen, phosphorus, magnesium, iron and calcium [5, 18]. In the final cultivation step nitrogen delivery is reduced to enforce lipid enrichment in the alga biomass [10]. The proliferation step in Erlenmeyer flags needs electrical energy for illumination, cooling, aeration, the orbital shaker and cleaning; for the cultivation in bubble columns energy is used for illumination, air conditioning and injection of CO_2; for cultivation in raceway ponds energy is needed to circulate the algae suspension by paddle wheels, for the injection of CO_2 and for the transfer of the alga suspension from one raceway pond to the next larger pond [5, 18].

Harvest consists of the following steps: preconcentration, cell disruption and dewatering [18]. Centrifuges rise concentration of algae C_B from 1.3 g DM l^{-1} to 100 g DM l^{-1} (total suspended solids (TSS) from 0.13 % to 10 %). . A promising method to accede the cell water is the destruction of membranes by electroporation [16, 20, 21]. The treatment under high voltage produces holes which are permeable only for water molecules [16]. Final solid-liquid separation must remove interstitial and intracellular free water to separate the concentrate of oil-rich biomass using disk separators from the preconcentration step.

Tab. 2: Energy inputs and operational materials normalized to 1 kg DM for the cultivation and harvesting steps [2, 18, 23, 28]

Process step	Amount per 1 kg DM	Unity
Laboratory Cultivation		
Electric energy	8,578	kWh
Fertilzer	$2{,}1 \cdot 10^{-4}$	kg
Fresh water	0,228	kg
Raceway ponds		
Electric energy	0,802	kWh
Fertilzer	0,729	kg
CO_2	2,6	kg
Fresh water	564,4	kg
Preconcentration		
Electric energy	1,1	kWh
Electroporation		
Electric energy	0,417	kWh
Dewatering		
Electric energy	0,0125	kWh

3.2 Raw material extraction and refinement

After dewatering the process chain splits into several lines ultimately leading to the final products (BtL, CtL or HVO). Existing procedures of raw material extraction and refinement are drying, carbonization, chemical or mechanical oil extraction (Fig. 2). In the following we describe properties, energy input and operational materials of the different production paths according to the scheme in Fig. 2 (i.e., from left to right).

Drying

BtL procedures have been conceptualized for the conversion of timber and wood chips into a synthetic fuel.

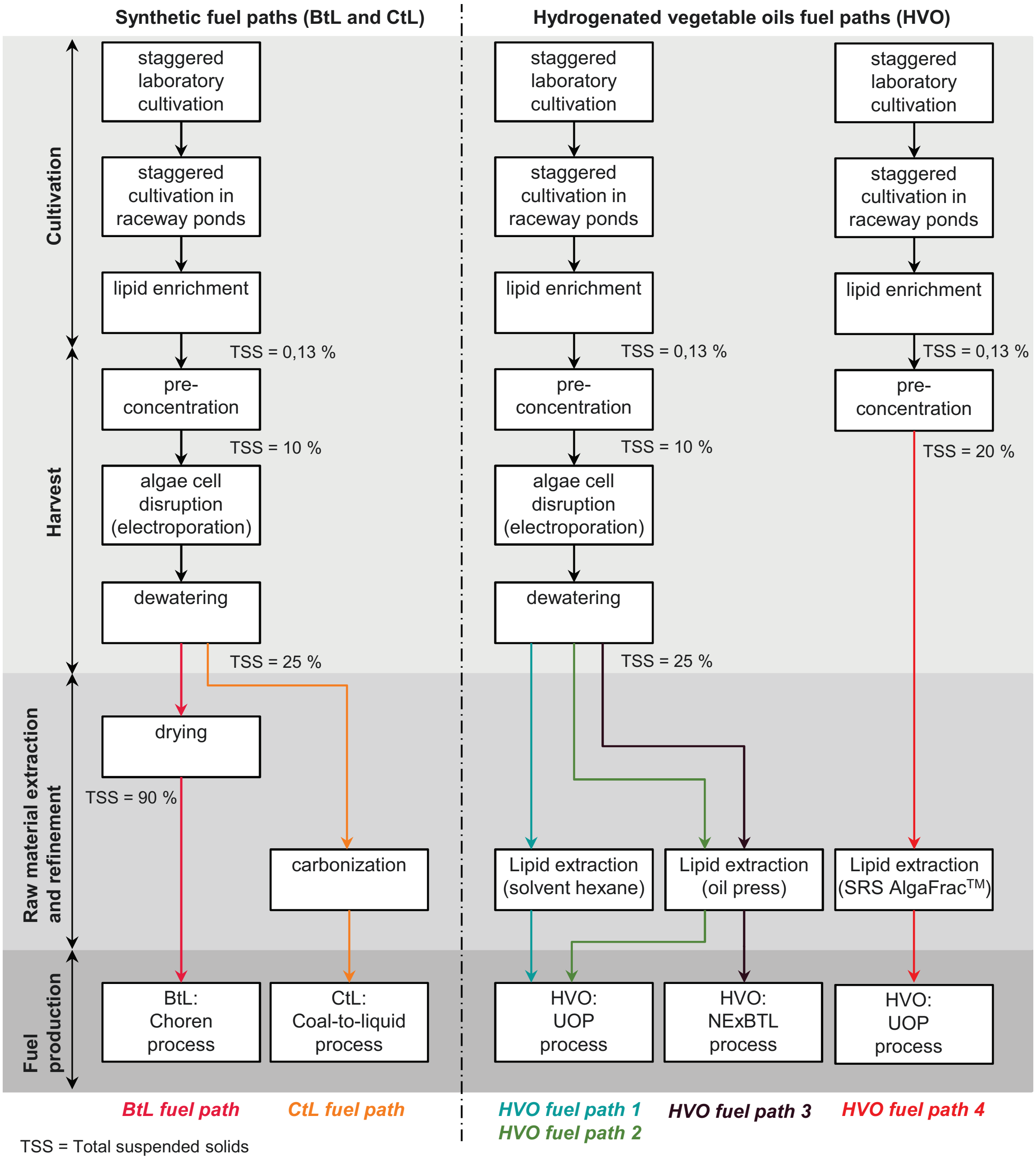

Fig. 2: Different fuel production paths of BtL, CtL and HVO from microalgae

BtL conversion is expected to work on a mean residual moisture of wood chips of 15–25 % [40]. Using algal biomass with a residual moisture of 75–85 % (TSS = 15–25 %) [44] after dewatering probably requires an additional drying step (BtL fuel path in Fig. 2). Drum drying is one possible method to reduce moisture to 5–10 % [6, 45]. The production of 1 kg DM involves an electrical energy input of 0.193 kWh, a thermal energy demand (from methane) of 1.889 kWh and 8 kg cooling water [6].

Carbonization

Problems involved in converting algal biomass into BtL are a) the residual moisture, and b) the small size of the microalga *Auxenochlorella protothecoides* (2–12 $\mu\mathrm{m}$) [22]. Carbonization (CtL fuel path in Fig. 2) overcomes these restrictions because it produces large dry particles (biocoal) and thus is an eligible process. In the carbonization procedure algal biomass is treated with water vapour at temperatures between 250 and 400 ℃ to obtain a cake of biocoal resembling commercial brown coal [38]. The process is known as biomass stream processing (BSP). A pilot facility at KIT in Karlsruhe has a reactor volume of 93 l, a throughput of 20 kg biomass h^{-1} [38]. Using published parameters, density and specific enthalpy of water vapour at 300 ℃

results in an energy demand of 0.03 kWh to produce superheated steam for one reactor filling. 1 kg biomass converts into 0.4 kg biocoal and 0.106 kg biooil [14,38].

Lipid extraction

HVO processes commonly start after dewatering and are mainly based on chemical extraction typically using hexane as solvent or mechanical extraction using oil presses (HVO fuel paths 1 to 3 in Fig. 2). Chemical extraction according to the Soxhlet method (HVO fuel path 1 in Fig. 2) works on hexane [37] with an extraction efficiency of 95 % [15] and requires electrical and thermal energy; for *Auxenochlorella protothecoides* with an measured oil content of 28.3 % [5] the energy demand according to [26] splits into 0.259 kWh for electrical and 3.42 MJ for thermal energy per kg oil. Hexane is being mainly recycled; the balance therefore only contains the amount related to the operating loss (0.0064 kg per kg oil) [26]. Additional outputs per kg oil are 0.02 kg oilcake which is recycled into energy re-used within the balance (see sec. 3.4) and 0.003 kg waste oil [26]. A special oil press of GFE Global (Typ 90) adapted for microalgae with an extraction efficiency of 94 % consumes 0.603–0.947 kWh electrical energy per kg oil depending on the throughput of the oil press [19]. Outputs are biomass (oilcake) and residual water; the biomass is recycled into energy re-used within the balance (see sec. 3.4).

A particular method of lipid extraction starts after preconcentration but involves complex additional procedures consisting of pretreatment, extraction, solvent recovery, oil separation, belt filter press and feed dryer (SRS AlgaFrac^{TM} system; HVO fuel path 4 in Fig. 2) [34,47]. Concentration increases from 1,3 g DM l^{-1} to 200 g DM l^{-1} in the preconcentration step (different to sec. 3.1 of 100 g DM l^{-1}) [34]. The extraction efficiency of this wet extraction method is assumed to be 100 %. Using detailed data from literature [34,47] 3.53 kg of algal biomass, 2.21 kWh electrical energy, 20.5 MJ thermal energy, a hexan loss of 0.0038 kg and 0.08 kg of an unspecified chemical are necessary to produce 1 kg oil. Additional outputs are 1.86 kg oilcake, 0.67 kg low value lipids, and 17.35 l waste water. The unspecified chemical can not be simulated. The oilcake as well as the low value lipids were recycled into energy re-used within the balance (see sec. 3.4).

3.3 Fuel production

In the final step oil-rich biomass is transformed into BtL (Choren process, BtL fuel paths in Fig. 2), biocoal into CtL (CtL process, CtL fuel path in Fig. 2), lipids are converted into HVO (UOP process, HVO fuel paths 1, 2 and 4 in Fig. 2) and lipids are converted into HVO (NExBtL process, HVO fuel path 3 in Fig. 2). The fuel production paths largely differ with respect to inputs and outputs and also involve different operation procedures.

BtL – Choren process

The raw material for the Choren process consists of wood chips but usage of algal biomass might be possible if additional drying is applied. We assume that particle size of the biomass is not important and that the difference in the calorific value H_u can be neglected (H_u of wood chips is 14.5 MJ kg^{-1} [39]). The Choren process includes low-temperature gasification, syngas production, gas conditioning, Fischer-Tropsch synthesis and fuel conditioning [39]. Inputs are NaOH, methanol, amines and catalyst(s) [39]. The economic outputs are Btl and electric energy. Using detailed data from literature normalised to 1 kg BtL results in a gain of 0.286 kWh of electrical energy and creates waste products (0.014 kg slurry) and emissions such as sulphur, SO2, and gaseous non-methane hydrocarbons [39].

CtL – CtL process

The Ctl process includes gasification of coal to syngas and the Fischer-Tropsch synthesis [1,41]. Within the Ctl process 7.4 kg biocoal are necessary to produce 1 kg CtL fuel, 0.322 kg naphtha and 1.727 kWh energy [1]. Inputs are oxygen, nitrogen, methane and water; outputs are compressed CO_2 and ash (see the amounts of the input and output in [1,41]).

HVO – UOP process

HVO was modelled on the hydrogenation process for soya oil developed by UOP analysed in [25]. Due to the lack of literature data we assume that the process data valid for soya oil hydrogenation can be applied as well to algal oil hydrogenation because chemical properties of the oil are identical [15]. The biooil is fed into a hydrotreater, where hydrogen and steam are added and the biooil is converted into hydrocarbons. This process requires 0.061 kWh electrical energy, 0.196 MJ steam, and 0.032 kg hydrogen to produce an output of 1 kg of HVO fuel and re-usable fuel gas (propane, 4.43 MJ) [25].

HVO – NExBTL process

HVO can be also modelled following the NExBTL process of the Neste Oil Corporation [17]. Process data are obtained from their production plant in Provoo (Finland). The Institute of Energy and Environmental Research Heidelberg GmbH adapted the Provoo NExBTL plant process data to European conditions [17]. The NExBTL process includes pretreatment and hydrotreating of the oil [17]. 1.22 kg algal oil are necessary to produce 1 kg HVO fuel, 0.010 kg re-usable naphtha and 2.81 MJ of fuel gas as well as 0.3 MJ sludge [17].

Inputs during pretreatment are H_3PO_4 and NaOH; during hydrotreating hydrogen, catalyst, electrical energy and steam are added. The fuel gas is recycled by a steam reformer to hydrogen and the sludge is converted by a boiler to steam [17].

3.4 By-products of the raw material extraction and refinement step

Oilcake is converted into electrical and thermal energy. The heat and power station commonly works on waste wood generating 0.747 kWh electrical and 0.335 kWh thermal energy from 1 kg of waste wood [46]. We assume that the usage of algal oilcake is also possible. Waste oil is converted into electrical and thermal energy by the use of a power station with an efficiency of 86 % and an oil consumption of 8.3 l h^{-1} [31]. 3.239 kWh electrical and 5.312 kWh thermal energy are produced from 1 kg of oil [31].

4 RESULTS

4.1 Primary energy demand

Fig. 3 details the distribution of the primary energy demand to produce 1 kg BtL, 1 kg CtL or 1 kg HVO fuel along the different steps. The cumulative primary energy demand for the complete fuel paths details as follows:

- BtL fuel path: 893.5 MJ per kg fuel
- CtL fuel path: 2038.8 MJ per kg fuel
- HVO fuel path 1: 494.3 MJ per kg fuel
- HVO fuel path 2: 494.1 MJ per kg fuel
- HVO fuel path 3: 517.4 MJ per kg fuel
- HVO fuel path 4: 462.6 MJ per kg fuel.

Fig. 3 shows that figures corresponding to the cumulative primary energy demand of fuel production (KEA_{P}) in HVO paths 1 to 4 are in the same order of magnitude (around 500 MJ per kg fuel). This is explained by the characteristics of HVO production holding almost identical conversion rates from fresh matter (FM) to 1 kg of HVO fuel (Tab. 3). In addition, cultivation and harvesting processes also need a similar amount of primary energy and HVO production processes (UOP and NExBTL) do not differ significantly. HVO fuel path 4 has the lowest (KEA_{P}) because the by-products (BP) biomass and low-value lipids of the SRS AlgaFrac$^{\mathrm{TM}}$ process yield a considerable amount (61.5 MJ per kg fuel) of secondary energy. In contrast, KEA_{P} of the BtL fuel path is twice as high as in HVO production path 1 to 4 and the KEA_{P} of the CtL path is even four times higher. The main reason for this large discrepancy is the conversion rate inside the production path: whereas 59.5 kg FM are necessary to produce 1 kg BtL fuel an input mass of 185 kg FM is needed for 1 kg Ctl fuel (Tab. 3). An outstanding feature of our results is the astonishing amount of primary energy demanded by laboratory cultivation; it markedly surpasses all other demands. A detailed look at the production steps listed in Fig. 3 reveals that the CtL fuel path is by far the most energy-intensive way to create fuel. The reason behind this lies in the masses involved (Tab. 3). CtL fuel path needs a laboratory input (expressed in MJ per kg fuel) which is higher by a factor of 4 in comparison to the HVO paths. Fig. 3 also shows that the energy needed for cultivation in raceway ponds, lipid enrichment, preconcentration, electroporation and drying is higher than the cumulative energy demand for fuel synthesis ranging only between 0.4 and 10.7 MJ per kg fuel. Credits for energy produced are highest in the CtL fuel path which again is a consequence of the masses involved.

Tab. 3: Distribution of conversion rates along different production paths to produce 1 kg biofuel from microalgae

Products	BtL	CtL	HVO 1	HVO 2	HVO 3	HVO 4
kg FM	59.5	185	44.37	44.1	46.2	41.5
kg DM	5.95	18.5	4.37	4.41	4.62	4.15
kg biocoal	-	7.4	-	-	-	-
kg oil	-	-	1.17	1.17	1.23	1.17
kg fuel	1	1	1	1	1	1
kg BP[a]	-	0.322[b]	0.097[c]	0.097[c]	0.010[b]	0.097[c]

[a] By-products of the fuel production process
[b] Naphtha
[c] Fuel gas

4.2 Net enery ration and CO_2-equivalent

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 cumulative non-renewable portion of the primary energy demand involved in production ($KNRA_{\mathrm{P}}$) with the calorific value (H_{u}) of a product [32]

$$(1) \quad NER = \frac{KNRA_{\mathrm{P}}}{H_{\mathrm{u}}}.$$

Consequently, a process is economically reasonable when NER is < 1 because less energy is required for production than stored in product. If the NER becomes < 0, energy is gained during the entire production process. The cumulative non-renewable demand $KNRA_{\mathrm{P}}$

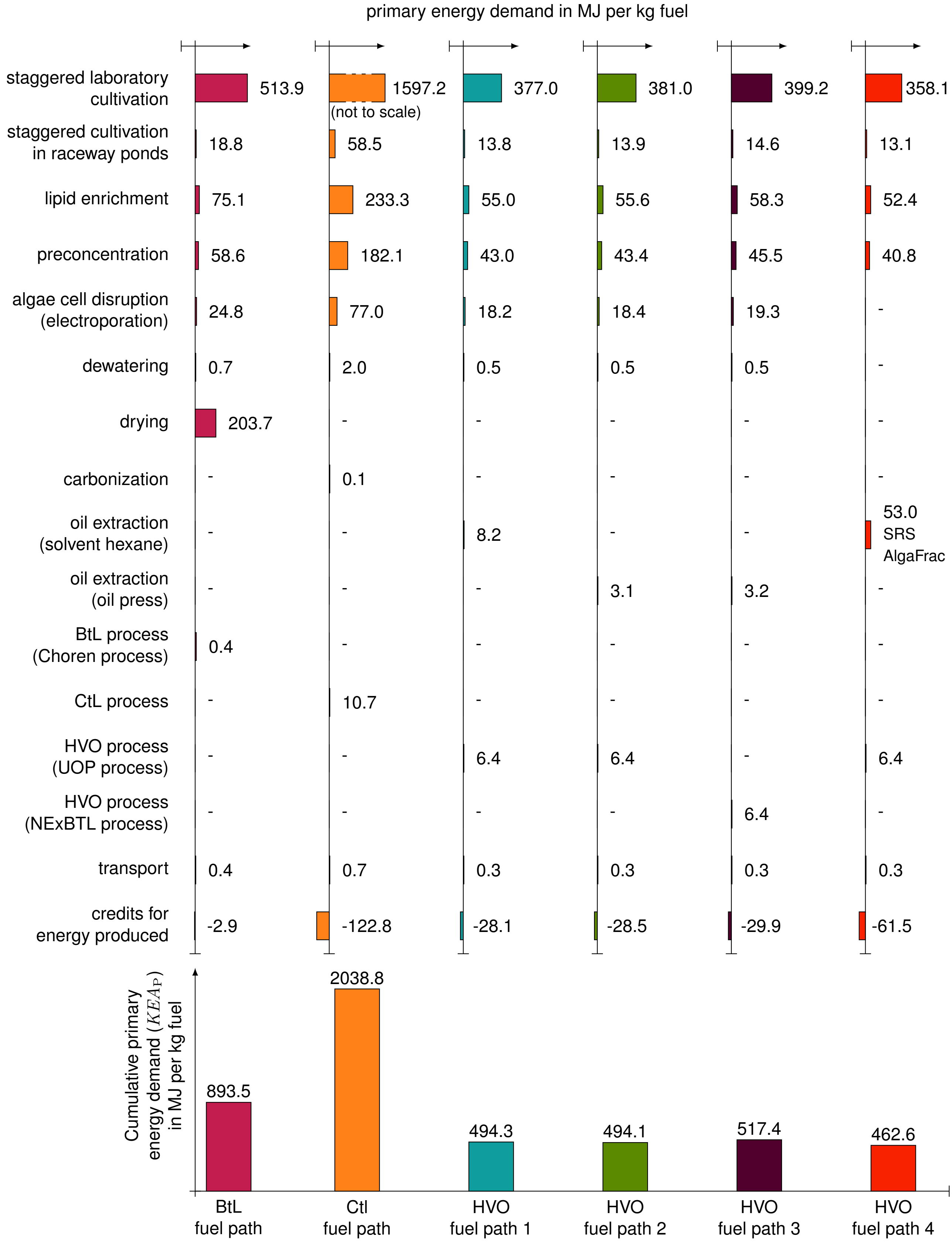

Fig. 3: Primary energy demand of individual production steps and cumulative primary energy demand of the complete Btl, Ctl and HVO paths in MJ per kg fuel. Note change of scale at the laboratory cultivation step of the CtL fuel path!

is calculated as the difference between the cumulative primary energy demand of the fuel production KEA_P and the cumulative renewable demand KRA_P [48]

$$(2) \quad KNRA_\mathrm{P} = KEA_\mathrm{P} - KRA_\mathrm{P}.$$

In Tab. 4 the NER and the $\mathrm{CO_2}$-equivalents per kg fuel for the different fuel production path (BtL, CtL and HVO) are plotted against different sources of electric energy. It is most remarkable that under current production conditions (e.g., European electricity mix) synthesis of biofuel from microalgae is inherently uneconomic unless renewable sources of energy are used. Performance of the BtL process is uneconomic ($NER > 1$) in all combinations presented in Tab. 4. When values are directly compared with the LCA data of 1 kg kerosene ($NER = 1.2$ [36]) almost all paths (excluding BtL) are only economic if regenerative sources of energy are applied; in comparison to kerosene these paths are increasingly competitive and perform best when using hydroelectrically generated energy.

The CO_2-equivalent (CO_2-eq) of kerosene is 0.395 kg per kg kerosene [36]. From this perspective all fuel production paths perform unfavourable when conventional electrical mix is applied. Usage of regenerative sources makes almost all paths economic but the BtL path again lags behind becoming feasable only if hydroelectrically generated energy is put in.

Tab. 4: NER and CO_2-equivalent (CO_2-eq) per kg fuel of fuel production paths compared to different sources of electric energy. Note the differences to the values of kerosene ($NER = 1.2$, $CO_2\text{−eq} = 0.395$).

	BtL	CtL	HVO 1	HVO 2	HVO 3	HVO 4
KEA_P [a]	893.5	2038.8	494.3	494.1	517.4	462.6
$KNRA_\mathrm{P}$ [a]	785.4	1735.5	423.1	422.2	442.2	197.1
European electricity mix						
NER	17.8	40.8	9.6	9.6	10.1	9.0
$\mathrm{CO_2}$ [b]	32.4	64.7	14.4	14.2	14.8	13.4
Photovoltaic energy as electric energy						
NER	5.8	4.5	1.3	1.2	1.2	1.0
$\mathrm{CO_2}$ [b]	3.3	-20.4	-5.9	-6.3	-6.6	-6.1
Wind energy as electric energy						
NER	4.8	1.5	0.6	0.5	0.5	0.3
$\mathrm{CO_2}$ [b]	0.4	-28.9	-7.9	-8.3	-8.8	-8.0
Hydoelectric energy as electric energy						
NER	4.7	1.1	0.5	0.4	0.4	0.2
$\mathrm{CO_2}$ [b]	0.2	-29.4	-8.0	-8.4	-8.9	-8.1

[a] in MJ per kg fuel
[b] $\mathrm{CO_2}$-equivalents in kg per kg fuel

5 CONCLUSION

This study demonstrates that at the present stage of technology production of biofuel from the fresh water microalgae *Auxenochlorella protothecoides* (Btl, Ctl and HVO) is far from environmentally neutral or positive. Unless primary energy input stems from renewable sources the balance is problematic throughout, either as a consequence of poor energetic performance or because of simulated theoretical paths of process engineering which concurrently are not realized even as pilot plants. Industrial-size plants for the production of biofuel from microalgae do not exist until today. Modelling is based on data from literature focused on laboratory and pilot plants; concepts for non-existing but feasible processes are theoretically synthesised. Among the different concepts of biofuel production from microalgae there is no economic competitive to conventional kerosene. However input from regenerative energy sources renders almost all paths (CtL and HVO paths) economic. The BtL path remains energetically ineffective; its CO_2-equivalent is better than those of kerosene only if hydroelectrically generated energy is used. In almost all cases the amount of primary energy demanded by laboratory cultivation is astonishingly high. It is remarkable that in all studied cases the energetic balance in the initial steps of fuel production (cultivation to raw material extraction) surpasses the amount involved in subsequent refining. We suspect that the high demand created by this initial production step might be an artefact of scaling when parameters of laboratory, pilot plant or theoretical processes are adapted to industrial dimensions. Unless hard data become available on at least one complete fuel production plant for microalgae fuels strictly designed to fulfil the criterion of minimal energy consumption and CO_2 emission our results must be considered as preliminary.

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