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

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ABSTRACT: The search for alternative fuels to alleviate our dependency on fossil-based transport fuels is driven by depleting conventional oil resources and looming climate change induced by anthropogenic greenhouse gas (GHG) emissions. Through a lifecycle approach, we evaluate whether algal biodiesel production can be a viable fuel source once the energy and carbon intensity of the process is managed accordingly. Currently, algae biodiesel production is 2.5 times as energy intensive as conventional diesel and nearly equivalent to the high fuel-cycle energy use of oil shale diesel. Biodiesel from advanced biomass can realise its inherent environmental advantages of GHG emissions reduction, once every step of the production chain is fully optimized and decarbonised. This includes smart co-product utilization, decarbonisation of the electricity and heat grids as well as indirect energy requirements for fertilizer, transport and building material. Only if all these factors are taken into account is the cost of heat and electricity reduced, and GHG emissions fully mitigated.

1. Introduction

The search for alternative fuels is relentlessly under way with 90% of transport fuels being hydrocarbon sourced and uncertainty around depletion levels of conventional oil reserves mounting [1-7]. Global vehicle ownership is forecast to reach two billion in the near future [4] and climate change concerns, induced by anthropogenic GHG emissions, expected to rise [8-10]. Liquid fuels derived from gas, coal or unconventional oil sources may be able to offset the input problem of diminishing oil supplies, but inevitably exacerbate the output problem of GHG emissions. Biofuels can be a viable substitute when produced in a sustainable manner and from feedstock which is not in direct competition with food or animal feed [11] notwithstanding problems surrounding the sourcing of sustainable feedstock as well as fertilizer run-off 12 and high water usage [13, 14.] The current state of Fischer-Tropsch (FT) fuel and ethanol production from cellulosic materials remains economically challenging with incremental improvements in lowering production costs [15].

Such concerns have highlighted interest in developing advanced biofuels from more favourable feedstock such as algae which overcome land use as well as food security issues [16, 17]. With microalgae's high production yields, the required global land mass necessary to satisfy fossil fuel consumption could be considerably reduced. For algae-derived biodiesel with a yield of 850 GJ/ha/y, to replace the current total production of 1.1 billion tons of petroleum-derived diesel per year, a land mass of 57,3 million hectares would be required which approximates to an area somewhat larger than Spain and smaller than Texas, see SI, Appendix S3. Microalgae can grow in waste or sea water, have vastly superior biomass yields per hectare[18, 19] and, most importantly, CO_2 removed from the atmosphere during photosynthetic growth of the plant offsets CO_2 released during fuel combustion [33, 34, 20].
Since it is most likely that within the next decades the share of transport fuels from energy intensive unconventional oil resources will increase, the production of advanced biofuels from microalgae can only be a viable renewable fuel source if the energy intensity of the process can be managed and lowered accordingly. The production of advanced biofuels from algae-sourced biomass is heavily dependent on direct and indirect energy inputs, and is not environmentally feasible at the moment.
Here we determine the life cycle energy balance and GHG emissions of producing microalgae (*Chlorella Vulgaris*) biodiesel compared to fossil diesel, the fuel to be displaced in the market. We estimate the fossil energy consumed and GHG emissions released at all stages of the production cycle, including feedstock farming (algae cultivation in open raceway ponds), biomass harvesting and drying, algae oil extraction, feedstock conversion (transesterification of algae oil into biodiesel), fuel distribution, and combustion by end user, see Figure 1. Outputs of the production process, which include biodiesel and fuel co-products in the form of oilcake and glycerol respectively, are all assigned with an energy content equal to the amount of energy released during combustion. The oilcake is derived from the algae oil extraction stage and glycerol is a co-product from the transesterification reaction (Figure1). Glycerol, here seen as end product, is refined and sold to the pharmaceutical industry or for use as livestock feed [21].

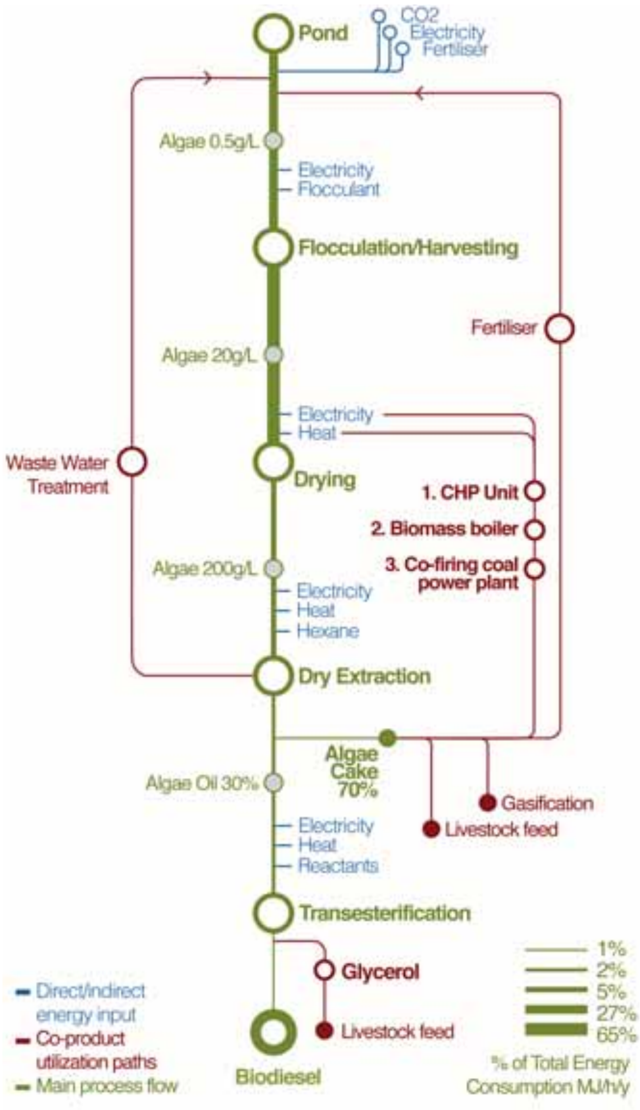

Figure 1 Energy flowchart of an algae-sourced biodiesel plant

For the algal oilcake, which stores 35%-73% of accumulated energy in the carbohydrate and protein content [18], we have considered three co-product utilisation options, which are: i) an adjacent coal-fired power system that co-fires biomass residues[22, 23]; ii) the direct combustion of oilcake in an integrated biomass-heating system [24]; or iii) in a biomass combined heat and power unit [25] (for further information see SI, Appendix 1). In addition we have conducted six nationally explicit life-cycle analyses for the UK, France, Brazil, China, Nigeria and Saudi Arabia. We compare GHG emissions and energy balance ratios by simulating the sourcing of primary energy and carbon intensity of the electricity and heat grids in each country. Our quantitative analysis is based on the status quo of different grids and the current feasibility of algae-to-biodiesel plants through a 'smart utilization' approach for the algae oilcake. Nevertheless, the overriding intention of our study is to analyse whether the algae-to-biodiesel production cycle demonstrates a future potential of becoming a relatively low carbon energy source, i.e. with GHG emissions considerably lower than conventional diesel. We therefore use the results of our base case and country specific life cycle analyses (LCA) to illustrate how changes to key input parameters affect the environmental feasibility of algae-sourced biodiesel.

2. Results and Discussion

We investigate the fossil energy requirements of the algae-to-biodiesel production process to track the renewable nature of biodiesel from advanced biomass sources. The cumulative fossil fuel demand relative to the energy production associated with the algae-to-biodiesel fuel has been analysed via the fossil Energy Balance Ratio (EBR), here defined as:

$$\mathrm{EBR}=\frac{\text{Total fossil energy input (MJ)}}{\text{Total energy output (MJ)}} \qquad (1)$$

At a fossil EBR smaller than 1, the fuel product provides more energy than the fossil energy required during the production process.

Our lifecycle study for the algae biodiesel production process is estimated to yield 851 GJ/ha/year biodiesel, and co-products in the form of oilcake (689 GJ/ha/year) and glycerol (89 GJ/ha/year), based on the assumption of an initial 30% oil content (22.5 tons/ha/year). Our values highlight a conservative average within a high-low scenario of 60% to 15% oil share, which would result in a range of production volumes for biodiesel (1701 to 425 GJ/ha/year), oilcake (394 to 837 GJ/ha/year) and glycerol (179 to 44 GJ/ha/year). In the first instance, we conducted a hypothetical baseline LCA study, which considers that all energy is produced by fossil fuels and that biodiesel is the sole fuel product, with both glycerol and oilcake as waste materials. This yields an EBR of 3.22, which compares unfavourably with an EBR of 1.20 for conventional diesel from the United States (Figure 2).

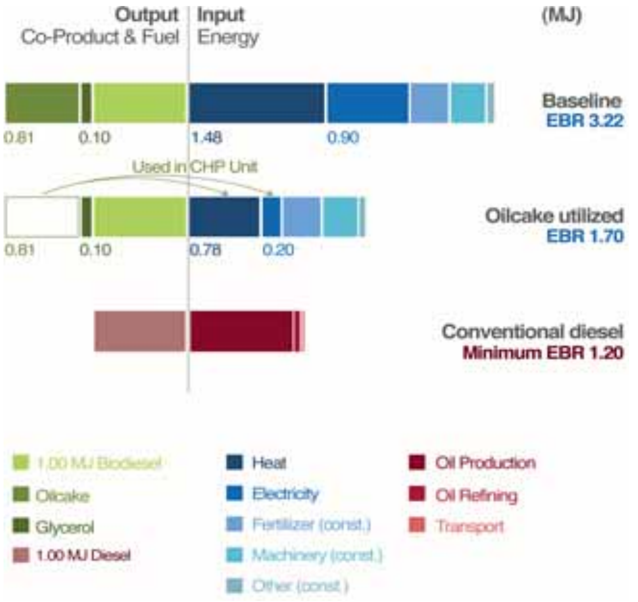

Figure 2: 1) Baseline LCA study excluding co-product utilization. Note: fossil EBR result only accounts for biodiesel energy output (MJ) and considers remaining co-products to be waste; Direct and indirect energy input is 100% fossil fuel based 2) Baseline LCA study incl.co-product utilization of oilcake through a CHP plant to offset heat and electricity demand; 3)Conventional diesel illustrated as benchmark.

This is the major disadvantage inherent in biodiesel production from microalgae, as energy input is both directly and indirectly needed for the production of fertilizers, pond, harvesting facilities as well as transport (see Supporting Text).

We note that an EBR of 1.2 for conventional diesel reflects the minimum fossil energy requirements for oil-based diesel production. The industry has become more energy intensive with unconventional oil resources from oil shale and tar sands already accounting for 12% of US crude oil production in the year 2000 [27]. As conventional oil resources become depleted, the larger uptake of unconventional resources, here in the form of shale oil, is reflected in a higher fossil EBR of 1.65 and GHG emissions around 182 g CO_{2eq}/MJ_{fuel} [27]. In addition to environmental degradation, the drawbacks associated with synfuel production from oil shale, are: the production cost, which is three times higher than conventional oil extraction; and considerable water usage of roughly 3 barrels of water per barrel of fuel produced [27]. Moreover, atmospheric emissions from oil shale processing can reach Well-to-Tank (WtT) emissions around 4 to 6 times the level of conventional fuels [27]. The expanding large-scale industrial application of advanced oil recovery practices, which account in the United States for 11% of total crude oil production [26]. The two most common enhanced crude oil extraction methods require the underground injection of natural gas powered steam or CO_2 to raise the pressure level of the oil well and force the crude oil to the surface. With the crude oil extraction stage attributing 93% of primary fossil energy demand, advanced oil recovery consumes twice as much primary energy and nearly 20 times more process energy than onshore conventional oil extraction. Since the amount of recoverable oil is lower than with conventional practices more electricity, which is most likely fossil based, is required per barrel of oil extracted [26]. In addition, the dependence on foreign oil production for most countries results in higher transport costs and lifecycle energy requirements for conventional fuels which will again increase the fossil EBR and carbon footprint of hydrocarbon-sourced transport system.

The inherent potential advantage of biodiesel production from algae is lower lifecycle GHG emissions. Algae biomass converts atmospheric CO_2 through photosynthesis into bio plant material, which is eventually released back to the atmosphere when used as a fuel, via engine tail pipe emissions. The cycle is illustrated in Figure 3.

In comparison, fossil fuel combustion releases additional carbon which took million of years to be removed from the atmosphere[26]. As we compare Tank-to-Wheel (TtW) (i.e. fuel consumption) GHG emissions for conventional diesel and biofuels, the fuel combustion stage accounts for the largest share of pollutants and CO_2 emissions. TtW GHG emissions for conventional diesel are around 73 g CO_{2eq}/MJ [28] assuming that the full carbon content of the fuel becomes CO_2 once combusted. This figure represents the inherent advantage of biofuel usage.

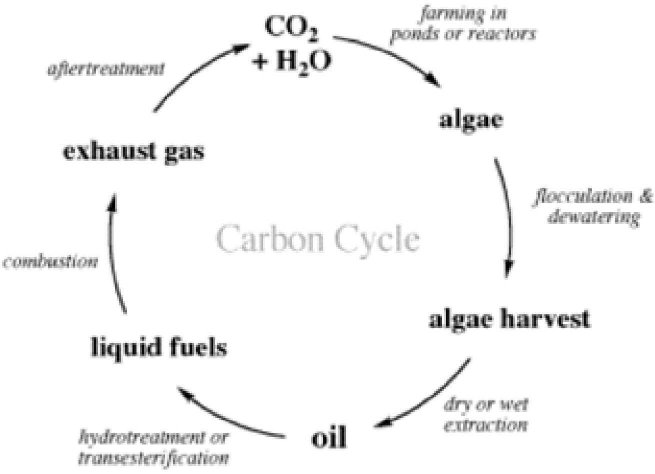

Figure 3 Carbon cycle of biodiesel production from algae biomass

Overall, GHG emissions for Well-to-Wheel (WtW) conventional diesel (i.e. comprised of feedstock cultivation, transport, fuel conversion, transport and fuel consumption), is in a range of 79 to 96 g CO_{2eq}/MJ with variations due to geographic electricity grid composition, transport mode and technology use [28].

Since the algae-sourced biofuel production is inherently, energy intensive, efficient energy management is critical. Here we focus on the carbon footprint. Varying the carbon intensity of the electricity grid affects the final carbon footprint of the algal fuel cycle. We first assume that the algal fuel cycle heat demand is supplied by natural gas and vary the carbon intensity of the electricity grid to determine the impact on the final GHG emissions ($gCO_{2eq/}MJfuel$). The results are shown in Figure 4. Our results have been benchmarked against WTW GHG emissions of conventional diesel and shale oil [6, 27, 28].

Four hypothetical cases have been created to illustrate the significant improvement in carbon footprint levels that can be achieved through co-product utilization, decarbonisation of the electricity and heat grid as well as all other indirect energy sources in each step of the process.

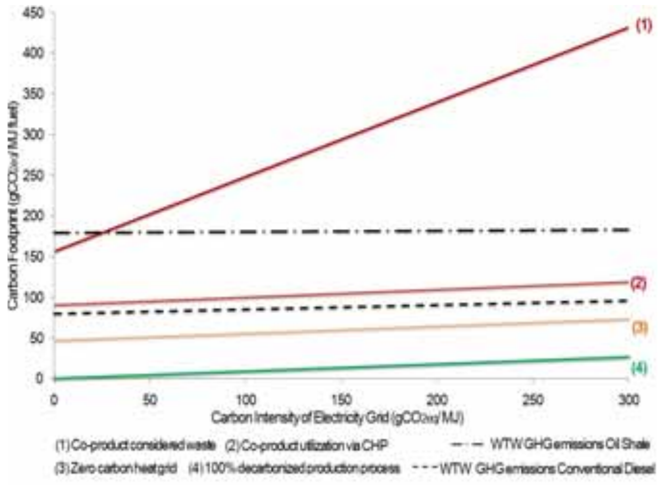

Figure 4 Sensitivity analysis highlights impact of carbon intensity of electricity grid on the final carbon footprint. Results are given for 1) algae fuel production with co-products considered waste; 2)co-product processed as part of a CHP unit; 3) heat grid is assumed to be fully carbon neutral. 4) All remaining indirect energy input is from low-carbon energy source. Data is benchmarked against EBR of conventional diesel and oil shale.

Figures for the first case, labelled as (1), are based on algal fuel production, with oilcake and glycerol as waste material. Under this assumption, the generation of algae-derived biodiesel would be highly unfavourable and increase GHG emissions regions where the carbon intensity of the electricity grid is high to around 450 gCO_{2eq}/MJ_{fuel} range. However, the second case (2) is more closely aligned with current production practices; here the oilcake product is utilised in a combined heat-and-power unit (CHP). Thus co-product utilization results in emission levels competitive with fossil fuels, when operated on a fully decarbonised electricity grid. By reducing the consumption of grid heat and electricity from 1.48 to 0.78 MJ/MJ and 0.9 to 0.2 MJ/MJ, the fossil EBR of 3.22 is lowered to 1.7, see Figure 2. However, the remaining high energy intensity of the algae biodiesel production cycle, when driven by fossil-based heat production and for fertilizer production, chemicals, machinery and transport still leaves a high carbon footprint.

In case (3), we take our analysis a step further, by assuming that the production cycle's heat requirements are fully met by a zero-carbon energy source, such as geothermal or solar. Now the algae-to-biodiesel production cycle has the potential to become a relatively low-carbon energy source in the future. Here, GHG emissions are considerably lower than petroleum-derived diesel figures, but are still limited by the high carbon intensity of fertilizer, chemicals, machinery and transport requirements. Consequently, in our fourth case (4), the algae-to-biodiesel fuel cycle is operated with fully decarbonised direct and indirect energy in addition to a smart utilization of oilcake residues within the process. The high carbon dioxide intensity of algae biodiesel is finally overcome. We note, however, that expense is determined by the inherently high energy intensity (EBR 3.22) of the process.

Country specific results

As part of our analysis, we focus on the current global potential for algae-sourced biodiesel, whereby six LCA studies for the UK, France, Brazil, China, Nigeria and Saudi Arabia have been conducted to determine a regional production preference, based on heat and electricity grid compositions from different primary energy sources, which as prior illustrated, impact the fossil EBR and GHG emissions level. Figure 5 illustrates the EBR breakdown for the algae biodiesel production with oilcake utilization through a CHP unit and ranks the results according to the country-specific share of fossil fuel based heat and electricity generation.

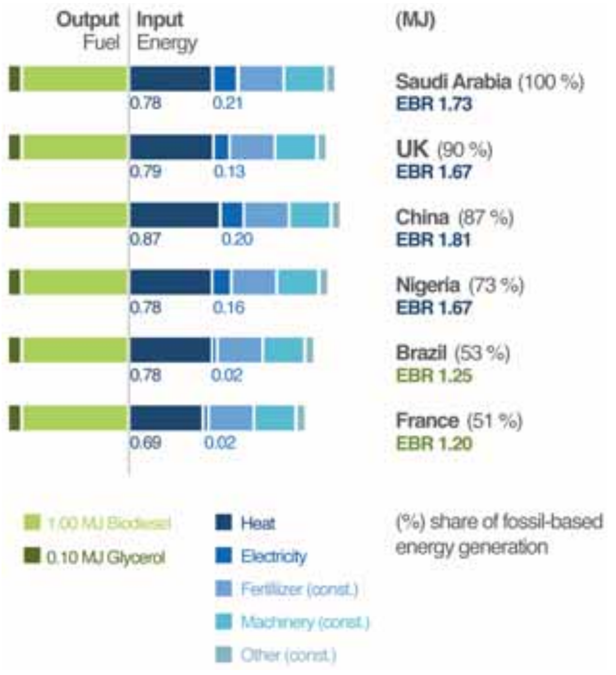

Figure 5 EBR results of six country scenarios. Countries are ranked by their share of fossil-based energy generation (*i.e.* heat and electricity). For Saudi Arabia, the UK, China and Nigeria oilcake is used in CHP unit. In Brazil and France the oilcake is directly combusted to offset natural gas powered grid heat, as a result EBR values are closest to conventional diesel.

Given the varying share of fossil-based energy generation in different countries, three types of co-product utilization are again considered to offer a 'smart allocation' approach to avoid the potential displacement of low-carbon primary heat and electricity generation. Our EBR results for all six countries, under the consideration of the three co-product utilization methods, are illustrated in Figure 6 and further benchmarked against studies by Lardon et al 18, who consider the algae oilcake to be processed outside the algae fuel cycle and exported as livestock feed. WTW GHG emissions for all countries, are shown in Table 1. Results for the oilcake use via a CHP unit are used to compile results for the second (2) trend line in Figure 4. The figures are compared with WTW GHG emissions from conventional diesel and unconventional shale oil.

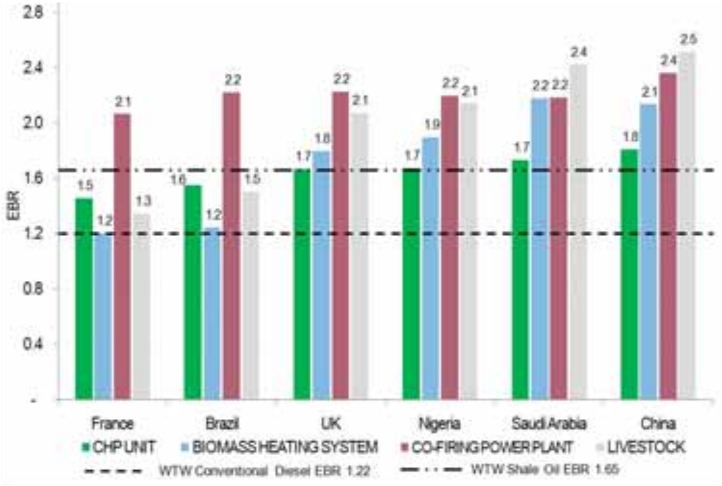

Figure 6 EBR results for algae-to-biodiesel production with following co-product utilization methods: 1) CHP unit ; 2) Biomass heating system; 3) Co-firing coal power plant; 4) Export as livestock feed 28. Figures are rounded to the next decimal place. Data is benchmarked against the EBR of 1.2 for petroleum-derived diesel and shale oil.

Table 1: GHG emissions (CO_{2eq}/MJ_{fuel}) of algae biodiesel production including co-product utilization via three different processes

	CHP	Direct Combustion	Co-firing power plant
China	160	351	260
UK	118	177	172
France	102	**78**	147
Brazil	109	**82**	160
Nigeria	114	180	152
Saudi Arabia	122	302	154
WTW Diesel	**79- 96 CO_{2eq}/MJ_{fuel}**[6, 28]		
WTW Shale Oil	**182 CO_{2eq}/MJ_{fuel}**[27]		

Not surprisingly, countries with a high share of hydrocarbon-based primary energy sources onto electricity grids would eliminate the environmental benefits of alternative fuels production. The objective for such countries remains to mainly improve the energy and environmental results, rather than achieve energy parity with conventional diesel.

3. Methods

Environmental Effects. In our study the functional unit is defined as 1 mega joule (MJ) of biodiesel produced from algae-oil. The stages of production, principal inputs required, and outputs produced are further described in SI and illustrated in a detailed energy flow chart in Figure 1. Given that at present no algal-oil-extraction plant is in large-scale commercial operation, the majority of process information is based on literature reviews and our own analysis. As part of the corresponding Life Cycle Impact Assessment (LCIA) section our work centres on the total global warming potential over a time horizon of 100 years and the total energy consumption in regards to the primary energy source used. All figures are analysed in both a baseline and country-specific context. Our LCA methodology is further used to calculate energy credits and the level of GHG emissions avoidance through the utilization of process' co-products, in our case algae residues. By applying the so-called displacement method [29], a co-product replaces a pre-existing input product and is utilized with a corresponding co-product credit. The credit is further reflected throughout the complete lifecycle GHG emissions and energy balance, as well as the production of the displaced input factor [29, 30]. Co-product credits are further subtracted from the overall LCA energy balance and carbon footprint, in order to complete the analysis. Details on three co-product utilization methods are given in SI, Appendix S1.

Algae strain selection and large-scale cultivation. In the approach advanced here, *C. vulgaris* algae is cultivated in open raceway ponds with an average size of 0.1 ha and a water volume of 0.03 m^3/ha. An initial algae biomass concentration of 0.5 kg/m^3 yields a wet algae biomass productivity of 24.75 kg/day for a cultivation site of 0.1 ha under typical operating conditions. We estimated for a dry algae biomass productivity of 75.0 tons/ha/year an average algae oil content of 30% and 70% oilcake [31], which is in line with earlier studies by Weyer *et al.*[32]. To facilitate the synthesis of algae biomass and their productivity levels, nutrients such as nitrogen in the form of ammonia (NH_3) and phosphorus in the form of superphosphate (P_2O_5) have to be supplied according to the algae cultures' stoichiometric requirements, (see SI, Table S2). Flue gases with a carbon dioxide content of 12.5 Vol.-% (the maximum value for a natural gas-fired power station [33]) from an adjacent power-plant have been assumed as a direct source of CO_2 [18, 34].
We note the substantial challenges involved in maintaining the mentioned biomass production yields in an open pond installation. Among other problems, the large-scale production of algae in open pond facilities faces the issue of likely culture contamination or collapse, poor light utilization efficiency, high water losses as well as immature harvesting technologies in consecutive stages. However, in this study, the water usage of the algae-to-biodiesel production chain has not been further analysed. Future research will focus on the development of a water and nutrient cycle, similar to Figure S3 as well as the recycling on nutrients through the reuse of harvest water as well as waste or seawater.

Building Material. The quantities of building material needed for the manufacturing of the open pond and harvesting facilities (*i.e.* pipes, paddlewheels, foundations, rotary press, *etc.*) were calculated to estimate the associated environmental burden for the construction of the production plant, see SI, Table S3.

Algae Biomass Processing and Conversion. The main stages considered in the algae biomass processing step are (i) flocculation, (ii) drying and (iii) algae-oil extraction. 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 vegetable oil extraction [18]. Following the flocculation and drying step, 75.0 tons/ha/y of dry algae biomass is obtained, a value in line with literature estimates found of 90.3 tons/ha/y [18], 75.0 tons/ha/y [32] and 40.0 tons/ha/y[16]. Algae oil can be separated from the biomass by dry extraction methods and is based on the soybean oil extraction method used by the GREET Transportation Model [30]. The 30% algae oil content and the remaining 70% of algae cake result in the production of 22.5 tons/ha/y of algae oil and 52.5 tons/ha/y of dry algal residue [32]. Further information is given in SI, Table S4-S5.

4. Conclusions

To be a viable substitute for fossil fuels, an alternative fuel should emit less GHGs than the fossil fuel it displaces, provide a net energy gain above the fossil energy input [35], operate on a defossilized heat and electricity grid, use all residual co-products within the cycle and be producible in meaningful volumes to impact on energy demand. This study is a quantitative assessment of all those factors and presents a major step towards a comprehensive understanding of the emissions and energy balance of algal fuels. These results are in direct agreement with our previous study on indirect emissions from electric vehicles, which showed a similar dependence of effective GHG mitigation potential on the carbon footprint of electricity generation [36].

We conclude that the energy intensity of the production process puts a large caveat on the financial and environmental feasibility of current algae biodiesel production. The production cycle’s economic running costs can be partially lowered by displacing costly grid heat and electricity through the smart usage of oilcake residues via a CHP unit and the utilisation of glycerol as livestock feed. The carbon footprint of the algae-to-biodiesel carbon cycle can only be minimized through the successful decarbonisation of the heat and electricity grid and the sourcing of all indirect energy requirements for fertilizers, transport and building materials, from low-carbon energy sources. As a priority, countries will need to defossilize primary energy sources used by their electricity grids, as only then can the transport sector move towards low GHG emissions. We have shown that countries such as China operating on a carbon-based electricity and heat grid, would eliminate the inherent environmental advantages of algal biodiesel, while Brazil and France which essentially operate on defossilized electricity grids, have the potential for biodiesel from algae to be a viable alternative to conventional diesel.

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