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The Carbon Footprint and Non-Renewable Energy Demand of Algae-Derived Biodiesel

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Abstract

We determine the environmental impact of different biodiesel production strategies from algae feedstock in terms of greenhouse gas (GHG) emissions and non-renewable energy consumption, we then benchmark the results against those of conventional and synthetic diesel obtained from fossil resources. The algae cultivation in open pond raceways and the transesterification process for the conversion of algae oil into biodiesel constitute the common elements among all considered scenarios. Anaerobic digestion and hydrothermal gasification are considered for the conversion of the residues from the wet oil extraction route; while integrated gasification-heat and power generation and gasification-Fischer-Tropsch processes are considered for the conversion of the residues from the dry oil extraction route. The GHG emissions per unit energy of the biodiesel are calculated as follows: 41 g e-CO_2/MJ_b for hydrothermal gasification, 86 g e-CO_2/MJ_b for anaerobic digestion, 109 g e-CO_2/MJ_b for gasification-power generation, and 124 g e-CO_2/MJ_b for gasification- Fischer-Tropsch. As expected, non-renewable energy consumptions are closely correlated to the GHG values. Also, using the High Dimensional Model Representation (HDMR) method, a global sensitivity analysis over the entire space of input parameters is performed to rank them with respect to their influence on key sustainability metrics. Considering reasonable ranges over which each parameter can vary, the most influential input parameters for the wet extraction route include extractor energy demand and methane yield generated from anaerobic digestion or hydrothermal gasification of the oil extracted-algae. The dominant process input parameters for the dry extraction route include algae oil content, dryer energy demand, and algae annual productivity. The results imply that algal biodiesel production from a dried feedstock may only prove sustainable if a low carbon solution such as solar drying is implemented to help reducing the water content of the feedstock.

Contents

1 Introduction

Despite tremendous improvements in the cultivation and processing of microalgae feedstock, the overall impact of algal biofuels on the environment upon widespread use has remained a highly controversial issue. The underlying elements that prevent a general analysis of such impacts are primarily attributed to the following: i) wide ranges of reported algae oil content and annual productivity, ii) lack of a proven technology for the extraction of oil from wet algae feedstocks or for solar drying of dilute algae slurries, iii) lack of information about the conversion of oil-extracted algae in biological and thermochemical processes alike, iv) lack of practical information regarding the extent to which nutrients can be supplied from wastewater or from a recycle stream within the biorefinery, and v) the inherent differences due to carbon and water sources, type of land, solar irradiance, and plant location and size.

A wide range of technologies concerned with the cultivation, harvesting, and conversion of algae into biofuels are currently under development. Beside this, extensive research is being undertaken to identify algae strains suitable for biofuel production, and to genetically modify these strains to improve their yields. Consequently, one would expect that any effort to extrapolate the environmental burdens of algae-derived biofuels in the future would be inevitably associated with a large degree of uncertainty. On the other hand, it is of crucial importance to determine the extent to which different algal biofuel production strategies can help mitigate the emissions and reduce our dependence on fossil fuels. Such insights would allow for comparing different technologies and subsequently guide the future research directions and resources towards the promising ones. These issues together clearly highlight the need to quantify the environmental impact of algal biodiesel under present uncertainties surrounding various aspects of algal biofuel production.

Generally, in order to account for any uncertain parameters or to consider the impact of future improvements that may occur in an emerging field such as algal biofuels, a local sensitivity analysis is performed to assess how the model output varies if a small change is made to any one of the input parameters. However, due to the highly non-linear behaviour of the model within the ranges over which these parameters can vary, the local sensitivity analysis is unable to capture the complexity of detailed models typically used in a life cycle assessment. In contrast, global sensitivity methods based on a random sampling over the entire ranges of all input parameters can be applied to fulfil this task [1], and to rank the relative contribution of each input parameter in a highly non-linear model. However, this method of analysis can be computationally intensive as it requires a large number of model evaluations.

Life cycle assessment is a widely used methodology for quantifying and examining the environmental aspects of biofuels. The analysis of well-to-wheel (WTW) carbon footprint of biofuels helps determine to what extent its widespread implementation can enable a country to reach its GHG reduction targets. Also, in principle, the carbon credit allocated to a specific biofuel should be proportional to the difference between the carbon footprints of the biofuel and fossil fuel to be displaced. A life cycle inventory for the WTW carbon footprint of algal biodiesel includes a credit for the sequestrated carbon dioxide, and GHG emissions from on-site activities and processes, embedded emissions in the raw materials and commodities (e.g. fertilisers, methanol, plant constructing materials, etc.), electricity

generation, and the combustion of the biofuel. A similar analysis would be also required to examine the WTW non-renewable energy consumption of the biofuel product. Only with a proper accounting of all these factors can one assess the true potential of algae-derived biodiesel in mitigating the GHG emissions and relieving our dependence on fossil resources.

Previous life cycle analyses of algal biodiesel have indicated potential environmental benefits over petroleum-derived diesel under certain circumstances [2, 3, 4]. In this study, we determine the well-to-wheel (WTW) greenhouse gas (GHG) emission and non-renewable energy consumption of different algal biodiesel production pathways. Both wet and dry oil extraction processes have been considered, each of which followed by different processes for the conversion of the oil-extracted algae, i.e. anaerobic digestion (AD) and hydrothermal gasification (HTG) for the conversion of wet extraction residue, and integrated gasification-power generation (CHP) and gasification-Fischer Tropsch (FT) for the conversion of dry oil extraction residue. Biomass drying was assumed to be carried out using a conventional belt dryer, or using a hypothetical process in which drying is assisted by solar energy. Subsequently, a global sensitivity analysis based on the High Dimensional Model Representation (HDMR) method is applied to determine the relative importance of each input parameter to the model outputs over the entire input space. Finally, the variation of the GHG emissions and energy balance ratios (EBR) with respect to two of the most influencing parameters, as identified by HDMR in the previous part, are investigated. The HDMR method is a highly powerful tool for the analysis of complex environmental models with a large number of input parameters. The global sensitivity analysis presented here covers several parameters associated with cultivation, harvesting, and downstream conversion processes of microalgae. Other general parameters such as the plant useful lifetime and the carbon intensity of the grid have been also taken into account.

2 Methodology

The production of algae-derived biodiesel is comprised of several consecutive steps: algae growth, dewatering, drying (if needed), oil extraction, oil esterification, and a process for energy recovery from the oil-extracted algae. In the following subsections, each of these process steps are briefly reviewed and the corresponding assumptions for each process are explained. The inputs to the LCA model were divided into two types: a) key process parameters which can vary over a specified range and b) fixed model parameters. The input parameters have been assigned to one of these two groups by mutually considering the extent to which each parameter was expected to affect the outputs, and the level of uncertainty surrounding that parameter. The key input parameters along with the range over which each one was allowed to vary in the HDMR analysis are given Table 1, while the fixed input parameters to each process are listed in their respective tables in the supporting information.

In this study, the non-renewable energy consumption has been reported in terms of energy balance ratio (EBR), which is defined as the ratio of the non-renewable energy consumption to the energy of the produced biodiesel over the entire life cycle and has the unit of

Nomenclature

AD	Anaerobic Digestion
CHP	Combined Heat and Power
EBR	Energy Balance Ratio
e-CO_2	Equivalent CO_2 Emission
FT	Fischer-Tropsch
GHG	Greenhouse Gas
GTL	Gas to Liquid
GSU	Gas Separation Unit
HDMR	High Dimensional Model Representation
HETA	Heat Exchanger Temperature Approach
HPS	High-Pressure Separator
HTG	Hydrothermal Gasification
HX	Heat Exchanger
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LPS	Low-Pressure Separator
MJ_e	Megajoule Electricity
MJ_b	Megajoule Biodiesel
MJ_f	Megajoule Fossil Energy
OEA	Oil-Extracted Algae
PBR	Photobioreactor
SSP	Single Superphosphate
Syngas	Synthesis Gas
VS/TS	Volatile Solid to Total Solid Ratio
WHSV	Weight Hourly Space Velocity
WTW	Well-to-Wheel

MJ_f/MJ_b.

2.1 Feedstock Production

The analysis presented in this study is focused on the production of algal biomass in open pond raceway systems. Briefly, each pond was assumed to be made of concrete (with no liner) and have an effective growth area of 1 ha. A paddlewheel is used to provide the agitation required for an optimal growth by maintaining an average water velocity whose range is given in Table 1. For the sake of improving the overall energy efficiency, the water velocity during the night time (e.g. 8 h/day) can be reduced to 80% of its value during the day time. The power consumption of the paddlewheel was calculated based on the sum of all head losses due to the channel walls friction, the bends at both ends, and the carbonation sumps. One should refer to [5] and Table S.3 in the supporting information for more details on the calculation of paddlewheel power demand.

The annual algae productivity and its oil content depend on several factors. Key amongst them are the algae strain, solar irradiance, temperature, nutrients availability, and growth system [6]. In the HDMR analysis, we assumed that the annual productivity and oil content fall within a range of 60–100 tonne/ha/year and 20–40 wt%, respectively. Although there exist a slight negative correlation between the algae annual productivity and its oil content [6], we have not considered this issue as the analysis herein presented is not based on a specific algae strain or production condition. Moreover, it was assumed that the entire amount of the algae lipids are used for the production of biodiesel, although strictly speaking, a small part of these lipids contain nitrogen and sulfur heteroatoms that render such molecules unsuitable for biodiesel production.

Another factor which can greatly affect the environmental aspects of algal biofuels is how the carbon and nutrients are supplied. In one scenario, carbon is provided through bubbling of a flue gas from a fossil-fuel power plant while nitrogen and phosphorus nutrients are provided via the addition of dedicated fertilisers (e.g. ammonia and single superphosphate). Depending on the downstream process for the conversion of algae into biofuel, it maybe possible to partially meet the nutrients demand though recovery of such compounds from the conversion residue and byproducts. In another scenario, the algae pond is fed with wastewater to provide the required carbon and nutrients. In this case, in addition to the produced biofuel, the treated water should be also considered as a product, and a proper accounting of the environmental impact of replacing a conventional wastewater treatment plant with an algae farm should be carried out. Although the second scenario may be more environmentally and economically viable, due to lack of useful information and the inherent complexities related to the variation of wastewater composition with respect to time and location, this study is limited to the case where the sequestration of carbon dioxide in flue gas is concerned. In such case, at a CO_2 mass fraction of 15%, a CO_2 to algae ratio of 2.0, and an algae oil content of 30 wt%, nearly 44 kg of flue gas has to be bubbled through the pond to obtain 1 kg biodiesel from the methyl esterification process.

2.2 Harvesting and Oil Extraction

One of the major barriers towards the production of algae-derived biofuels in an environmentally benign manner is the extremely low solid content of the feedstock in the culture medium (i.e. 0.05–2 wt%). The initial feedstock can be effectively concentrated up to nearly 10 wt% using physical precipitation methods with low energy demands (e.g. clarifiers, bioflocculation). However, due to the small sizes of solid particles and their water-like density, further dewatering and drying of the microalgae slurries becomes more and more challenging at higher concentrations. In the present analysis, it was assumed that the algae culture is first concentrated to 5 wt% using two consecutive clarifiers, which is subsequently increased to 20 wt% by centrifugation (see Table S.3). Several processes with a wide range of technology readiness levels and efficiencies exist for the extraction of oil from algae cells. Depending on the process requirement with respect to the moisture content of the feedstock, the algae oil extraction processes are generally categorised into the dry and wet methods. Typically, the dewatered algae feedstock (e.g. centrifuge precipitate) can be directly fed to the wet extraction processes which in turn separate the

oil as an immiscible organic phase while leaving the oil-extracted algae (OEA) in the aqueous phase. In contrast, the moisture content of feedstock has to be reduced to about 10 wt% prior to the extraction via dry methods. In this study, two scenarios were considered with respect to the drying of centrifuge precipitates: a case where the entire drying occurs in a gas-fired biomass dryer, and another case where the centrifuge precipitate is first concentrated to 26-36 wt% using solar energy and then fed to the dryer to reach a final concentration of 90 wt%. The gaseous fuel to the dryer could be partly or entirely generated from the conversion of OEA (i.e. methane from biogas, methane from hydrothermal gasification, and syngas from conventional gasification). If the algae-derived combustible gas is not enough to meet the energy demand of a conversion pathway with a given process arrangement, it was then assumed that the remaining energy is provided by natural gas. In the sensitivity analysis presented in this study, the heat-to-electricity ratios of the drying and extraction processes are kept constant, and the sum of the two parameters are collectively represented by the process energy demand in the results section. Further details about the wet and dry oil extraction processes considered in this study are given in Table S.4 and further information about dryer's energy demand can be found in [2, 7].

2.3 Conversion Strategies

An overview of the conversion strategies considered in this study is shown in **Figure 1**. The isolated algae oil can be converted into biodiesel via a transesterification process in which the reaction of algae fatty acids with methanol in presence of an alkali would yield methyl esters and glycerol. The transesterification process is relatively simple and high oil-to-biodiesel yields are often achievable. Due to its low economic value, it was assumed that the crude glycerol byproduct is converted into gas using the same process that is utilised for the conversion of OEA.

In contrast to the algae oil, the choice of conversion process for the realisation of OEA energy is not trivial. In a biofuel-only algal biorefinery, different scenarios are possible for such purpose, each of which can prove to be more environmentally benign depending on the upstream harvesting and oil extraction processes among several other factors. The OEA slurry from the wet oil extraction process can be converted to a mixture of methane, carbon dioxide and other gases using anaerobic digestion and hydrothermal gasification, or can be alternatively liquefied in near-critical water to yield bio-oil which can be further upgraded into liquid hydrocarbons. The solid OEA from the dry oil extraction process can be gasified to produce syngas, which can be subsequently fed to a Fischer-Tropsch (FT) reactor to produce more diesel fuel, or burnt to generate heat and electricity. Without underestimating other conversion strategies, this study is focused on the conversion of OEA via anaerobic digestion, hydrothermal gasification, gasification-combined heat and power (CHP), and gasification-Fischer-Tropsch (FT) processes. Schematic process flow diagrams of anaerobic digestion and hydrothermal gasification which are conversion of OEA slurry and gasification-CHP and gasification-FT for the conversion of dried OEA are illustrated in **Figures 2** and **3**. A list of fixed parameters for these processes are given in supporting information. For further information about these processes, one can refer to [8, 9] for anaerobic digestion, [10, 11] for hydrothermal gasification, [12, 13] for integrated gasification-CHP, and [14] for gasification-FT.

2.4 General Considerations

Depending on the total demand for external electricity, the life cycle GHG emission of algal biodiesel can be affected by the carbon intensity of the grid electricity to a variable degree [4]. This dependency can be suppressed by an on-site electricity generation using algae-derived gaseous fuels such as biogas and syngas produced from the conversion of the oil-extracted algae, or by utilising solar energy to generate electricity or reduce the water content of the feedstock. In the present study, the average grid carbon intensities of France (i.e. 30 g e-CO_2/MJ_e) and China (i.e. 340 g e-CO_2/MJ_e) have been used as the lower and upper bounds for the carbon footprint of the purchased electricity, respectively [15]. The lower bound considered for the grid GHG emission approximately applies to cases where the external electricity demand is fully provided by on-site power generation using renewable energies such as solar or wind. The EBR of grid electricity value was assumed at 3.6 MJ_f/MJ_e regardless of the electricity generation mix as it only varies within a relatively small range (see **Figure S.1**) [15]. Furthermore, it should be noted that in scenarios where the energy of OEA-derived gaseous fuel was insufficient to meet both thermal and electrical energy demands, the priority was given to maximum electricity generation through the adjustment of the CHP outputs.

For a given set of conditions regarding the cultivation and conversion of algae, the useful lifetime of the plant determines the total amount of biodiesel that the plant is capable to produce. Consequently, the carbon (and energy) footprint per kilogram of the biodiesel product that is associated with the construction of the plant would be indirectly affected by the plant lifetime. In this study, we assumed the plant lifetime lies between 20 to 30 years which represent a typical range for the chemical plants. Furthermore, as low carbon energy and commodities will become more predominant, one can expect that the embedded carbon footprint and the non-renewable energy associated with fertiliser, electricity, construction materials, etc. would decrease in the future. However, studying the potential influence of this issue lies beyond the scope of this study and requires further investigation.

In the presented analysis, the Intergovernmental Panel for Climate Change (IPCC) 100-year global warming potentials factors for methane and nitrous oxide were used (i.e. 25 and 298 with respect to carbon dioxide, respectively).

2.5 Global Sensitivity Analysis using HDMR

While the environmental impacts of a biofuel produced under a given set of conditions can be evaluated using a life cycle analysis approach, it is also of great importance to understand the relative sensitivities of the key environmental metrics to the process variables. An application of such information could be, for example, when a research group developing new strains of algae want to determine whether getting a higher annual biomass productivity or getting a greater oil content in the new strain can more significantly reduce the carbon footprint of the final algal biodiesel. Another example would be to assess the potentials for the reduction of GHG emissions of different algae conversion strategies in the future given the plausible improvements in the performance of different parts of the process.

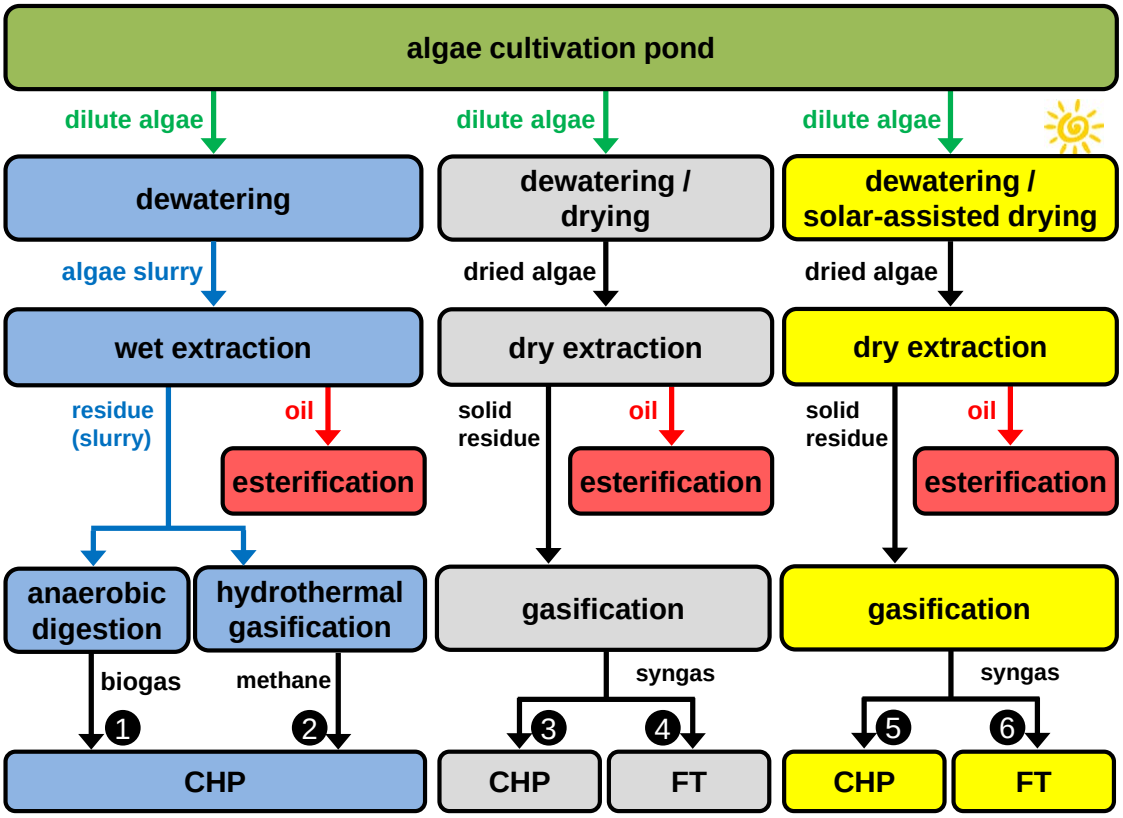

Figure 1: *Schematic process flow diagram of algal biodiesel production via wet extraction, dry extraction, and solar-assisted dry extraction with different strategies with respect to the conversion of the oil-extracted solid.*

In this paper, the global sensitivities of the carbon and non-renewable energy footprints of biodiesel production from algae are calculated using a High Dimensional Model Representation (HDMR) method. One advantage of the method used here to deal with non-linear models is that, unlike methods for local sensitivity analysis in which calculations are based upon local slopes, the whole space of the input variables is considered to calculate the global sensitivities in the HDMR method. This means that magnitude of the range over which each parameter is allowed to vary has also a direct effect on the sensitivity to that parameter. Moreover, global sensitivity analysis using the HDMR method not only takes into account the inherent uncertainties in the input parameters but also potential non-linearities and contributions due to interactions between input parameters. In this paper we use a Quasi-Random Sampling High Dimensional Model Representation (QRS-HDMR) method to simultaneously calculate global sensitivities and generate surrogate models [1]. This method has been previously applied to analyse the economic viability of algal biodiesel under technical and economic uncertainties [16].

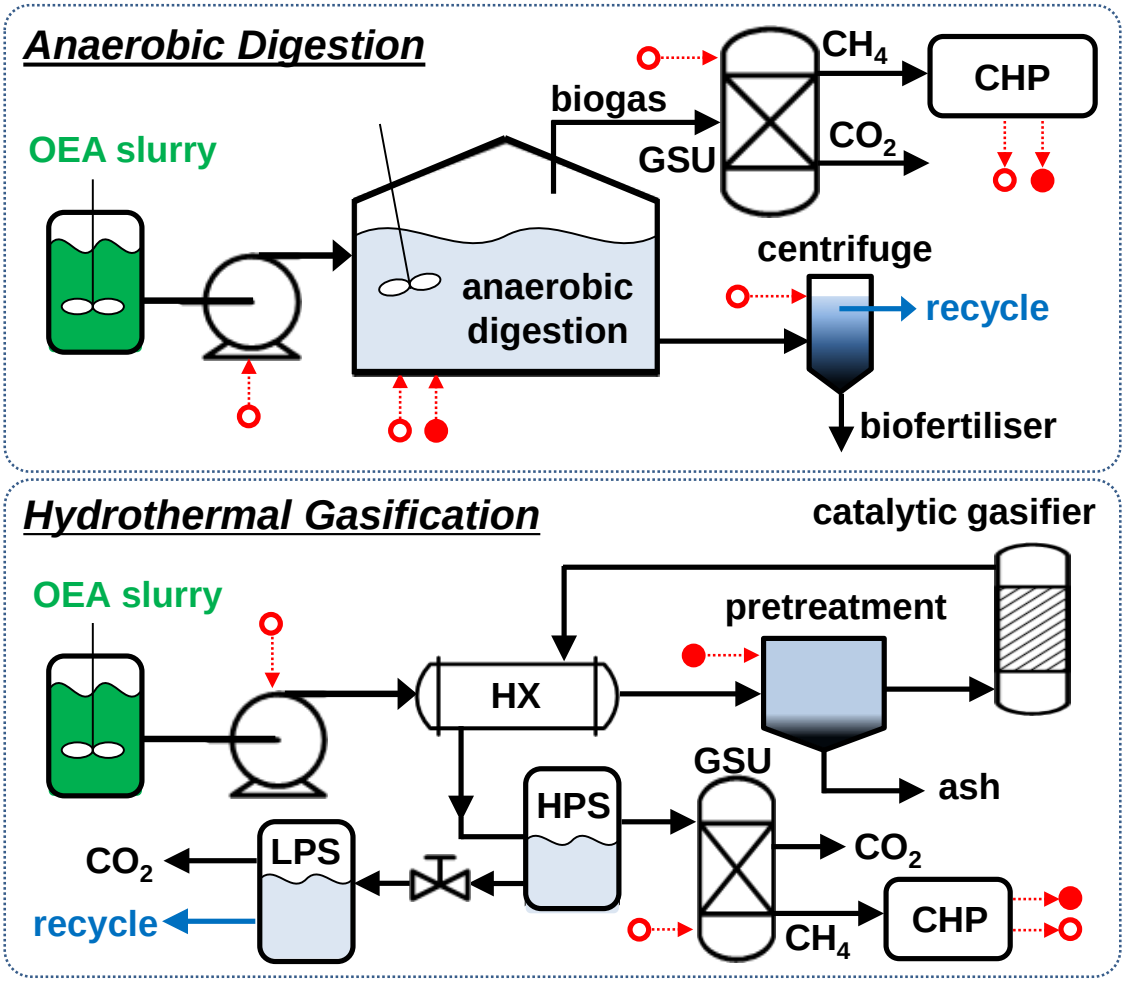

Figure 2: *Schematic process flow diagram of anaerobic digestion and hydrothermal gasification processes considered for the conversion of wet extraction OEA slurry. Open and filled circles represent electrical and thermal energy, respectively.*

3 Results

In all conversion pathways sketched in Figure 1, biodiesel is produced through the reaction of methanol with the extracted algae oil using transesterification process. However, as discussed earlier, the choice of a conversion process for the recovery of the energy content of the OEA is not trivial and would depend upon several economic and technical factors. In the present study, we solely focus on the environmental impacts of a such processes and compare a number of these processes in terms of their overall GHG emission and non-renewable energy consumption. In principle, two distinct approaches exist for the utilisation of the oil-extracted algae within a biorefinery, both of which increase the plant revenue and mitigate the overall environmental burdens that are associated with the main product (i.e. in this case biodiesel). In the first approach, the OEA is directly combusted in biomass boilers, or first converted into a combustible gas (via anaerobic digestion, hydrothermal gasification, and conventional gasification) and then combusted,

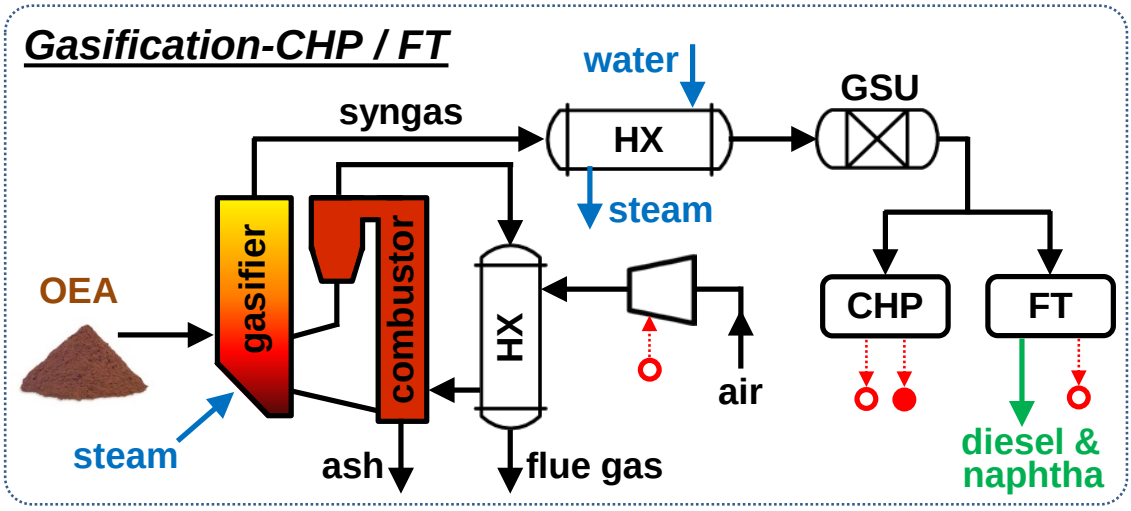

Figure 3: *Schematic process flow diagram of gasification-CHP and gasification-FT processes considered for the conversion of dry extraction OEA. Open and filled circles represent electrical and thermal energy, respectively.*

which would partially or fully meet the demand of the entire process. This would reduce or even eliminate the emissions associated with the supply of process heat and electricity from the national grid. The energy demand (excluding drying) for the conversion of OEA into combustible gases decreases with the following order: anaerobic digestion >hydrothermal gasification >conventional gasification.

In the second approach, the OEA itself is valorised into diesel through an intermediate generation of syngas, or used for other purposes such as an animal feed, the former of which could reduce the carbon footprint of the biodiesel product by increasing the overall biomass-to-algal diesel yield, where the algal diesel represent to the sum of biodiesel and synthetic diesel produced via oil esterification and Fischer-Tropsch, respectively.

In the following subsections, the mean GHG emission and EBR values associated with each conversion pathway are first presented. The environmental stressors are grouped into four classes: energy (heat and electricity), fertiliser, plant construction, and chemicals (methanol, hexane, etc.). In the next part, using the HDMR method, the sensitivities of the biodiesel GHG emission and EBR to the primary input parameters outlined in **Table 1** are discussed. Finally, the respective technical and policy implications to the findings of this study are discussed in detail.

3.1 Mean GHG Emission and EBR Values

The mean GHG emission and EBR values of the algae-derived biodiesel produced from different conversion strategies are depicted in **Figure 4**. The results presented in this figure are based upon the nominal values given in Table 1, while the error bars represent the standard deviation if the values of the input parameters vary over the ranges specified in the same table. In other words we assume that the input parameters in Table 1 are uniformly distributed over the range stated in the table. It should be noted that the break-

Table 1: *Ranges of parameters for global sensitivity analysis.*

Parameter	Nominal Value	Lower bound	Upper bound	Unit
Cultivation				
Algae productivity	80	60	100	tonne/ha/year
Algae oil content	30	20	40	wt%
Pond water velocity	0.25	0.20	0.30	m/s
Drying and Extraction				
Wet extraction				
Heat	4.5	2.2	6.8	MJ/kg algae
Electricity	0.50	0.25	0.75	MJ_e/kg algae
Drying				
Drying heat	3.5	2.8	4.2	MJ/kg water
Drying electricity	0.37	0.30	0.44	MJ_e/kg water
Solar drying	31	26	36	wt% solid
Dry extraction				
Extraction heat	1.3	1.0	1.6	MJ/kg algae
Extraction electricity	0.25	0.20	0.30	MJ_e/kg algae
Oil transesterification				
Heat	0.85	0.7	1.0	MJ/kg oil
Electricity	0.13	0.10	0.16	MJ_e/kg oil
Conversion of residue				
Anaerobic digestion				
Biogas yield	60	40	80	% of maximum
Biogas leak	2.0	0.0	4.0	% produced
Fertiliser recovery	75	60	90	%
Biofertiliser activity	40	20	60	%
Carbon sequestration	0.08	0.02	0.14	% added to soil
Hydrothermal gasification				
Carbon conversion	80	70	90	% produced
HETA	35	20	50	°C
Syngas generation				
Cold gas efficiency	0.85	0.80	0.90	%
Fischer-Tropsch				
Chain growth probability	0.85	0.80	0.90	
General considerations				
Plant lifetime	25	20	30	years
Grid emission	185	30	340	g e-CO_2/MJe

down values given for each category represent the net emission (or energy consumption) obtained by subtracting the energy and fertiliser recovery credits from their respective gross values. For comparison, the corresponding GHG emission and EBR values for the petroleum diesel and the gas-to-liquid (GTL) synthetic diesel are also given (see **Table S.1** in supplementary information). One should realise that the EBR values of greater than unity for the petroleum and GTL diesel are due to the energy consumption during extraction, transportation, refining, and conversion of the crude fossil fuels into the final product.

In general, both GHG emission and the EBR values of the algal biodiesel from the wet extraction routes are significantly lower than those of the dry extraction routes. Furthermore, it can be seen from this figure that the lowest GHG emission and EBR values are obtained when the OEA is converted via a hydrothermal gasification process. This is partly due to the surplus methane (or heat and electricity) that can be generated from the HTG products (i.e. methane, hydrogen), as indicated by negative values in Figure 4. Compared to the HTG process, anaerobic digestion results in considerably lower net methane yields as a relatively large part of the produced biogas is consumed on-site to provide the electricity and the heat demands of digester, centrifuge, and gas compressor. Based on the assumptions made in this study, these factors collectively account for nearly 57% and 21% of the gross heat and electricity outputs of the CHP unit, respectively. Nevertheless, considering the low capital cost, current industrial penetration, and the potential to recover a large part of the applied fertiliser, the anaerobic digestion process for the conversion of OEA may prove more economically viable compared to the catalytic hydrothermal gasification process.

The life cycle analysis revealed that the WTW emissions and EBR values of biodiesel from the dry extraction route are substantially higher than those from the wet extraction, and are even likely to be higher than conventional and FT diesel. This is primarily attributed to the high latent heat of water as reflected by the contribution of *energy* in Figure 4. In the case of OEA energy recovery through integrated gasification-CHP, 55% and 100% of the plant gross heat and electricity requirement can be supplied from the CHP unit, respectively. As an alternative to this scenario, the syngas generated from the gasification of OEA can be used to produce more diesel by the FT process. In this case, owing to the higher overall algae-to-diesel yield, the indirect emissions due to the plant construction and consumptions of fertilisers and chemicals are somewhat reduced. However, in contrast to all other conversion strategies considered in this study, no credit was accounted for the energy recovery from OEA for the gasification-FT route and, as a result, the contribution of the *energy* in both GHG emission and EBR were extremely high.

Since the wet extraction technologies are still at the early stages of development, the dry extraction process may, at least in the near to mid-term future, remain to be the only practical option for breaking the algae biomass into its constituent components. This would, in turn, necessitate to develop alternative solutions for reducing the carbon and energy intensities of each step involved in the production of algal biodiesel from a dried feedstock, particulary the drying process itself which is highly energy-intensive. To this end, solar energy inherently seems to be a viable choice to provide the plant with decarbonised heat and electricity as the biorefineries are likely to be located in areas that receive high solar irradiance [17, 18]. For example, if solar energy is used to increase

the solid content of the feedstock from 20 wt% (corresponding to centrifuge precipitate) to 31 wt%, a biorefinery plant based on the gasification-CHP route can become fully energy self-sufficient. This would, subsequently, reduce the GHG emission and EBR of the final biodiesel product from 109 g e-CO_2/MJ_b and 1.48 MJ_f/MJ_b to 59 g e-CO_2/MJ_b and 0.76 MJ_f/MJ_b, respectively. Using the same assumptions for the input and output concentrations of solar-assisted drying for the gasification-FT route, the overall emission and EBR of biodiesel would change from 124 g e-CO_2/MJ_b and 1.81 MJ_f/MJ_b to 87 g e-CO_2/MJ_b and 1.24 MJ_f/MJ_b, respectively.

Depending on the conversion strategy, the mean indirect emission due to the construction of the algae cultivation pond and the harvesting and conversion systems is responsible for 27-35 g e-CO_2/MJ_b, which typically corresponds to 30% of the emission from petroleum diesel. One should expect that with a more comprehensive accounting of the construction materials (and energy), these values are likely to rise.

3.2 Global Sensitivity Analysis

In this section, the results obtained from the global sensitivity analysis for different oil extraction strategies and their subsequent OEA conversion processes are discussed. For each combination of the oil extraction technology and the OEA conversion process, the relative influences of the input parameters on the GHG emission and EBR are ranked and presented in pie charts for comparison. It is worth emphasising that the global sensitivity herein calculated with respect to a parameter is indeed dependent on both the local response of the desired function to a small change in that parameter, as well as on the extent to which the desired output would change if that input parameter varies over its entire range.

3.2.1 Wet Extraction

Figure 5 shows the global sensitivity analysis of the GHG emission and EBR of the biodiesel when the OEA is converted into biogas in an anaerobic digester (*route 1*). In general, the algae oil content, oil extraction energy demand, and the yield of biogas from the OEA were found to be the dominant contributors. Concerning the GHG emission, the effect of the oil extraction energy demand substantially decreases by increasing the algae oil from 20 to 40 wt%. Also, for the algae oil contents of below 30 wt%, it seems unlikely that such conversion strategy allows for the production of biodiesel with a life cycle GHG emission lower than that of the conventional diesel (i.e. 91.7 g e-CO_2/MJ_b). Nonetheless, at high oil contents (e.g. >35 wt%), a slight to moderate reduction in GHG emission over the conventional diesel can be achieved. Compared to the GHG emission, the non-renewable energy consumption of the biodiesel production from this route is more attractive, as there is a fairly large range within which the EBR values of the biodiesel compares favourably with that of the conventional diesel. Moreover, the biogas yield seemed to have a constant effect on the EBR throughout the entire ranges both for the biogas yield itself and for the wet extraction energy demand.

The results obtained for the conversion strategy comprised of oil esterification and hy-

drothermal gasification (*route 2*) are depicted in **Figure 6**. In this case, the dominant parameters include oil extraction energy demand, gasification conversion, and algae annual productivity. Importantly, the algae oil content appeared to have virtually no noticeable effect on the environmental metrics considered here. This can be partly attributed to the high efficiency of energy recovery when the residues are converted into a methane-rich gas mixture, which is in turn combusted to generate heat and electricity. In other words, the algae composition would become a less influential parameter as the difference between the efficiencies of the processes utilised for the conversion of different algae constituent components becomes smaller. In fact, if all other parameters are kept constant at their mean values given in Table 1, the biodiesel GHG emission would only change from 39 to 45 g e-CO_2/MJ_b by varying the algae oil content from the upper bound (i.e. 40 wt%) to the lower bound (i.e. 20 wt%). An important implication of these results, albeit as long as the impact on the environment is the sole concern, is that the choice of algae strain should be made by focusing on the annual productivity and regional compatibility criteria. As can be seen in Figure 6, under almost any circumstances, both GHG emission and EBR values of biodiesel from this route are well below those of conventional diesel. In particular, if the oil extraction energy demand can be reduced to lower than 3.5 MJ/kg_{algae}, it would be possible in the future to produce biodiesel from this route with a well-to-wheel emission of 20 g e-CO_2/MJ_b or lower. In this case, even if the algal biodiesel is used as a blending agent to the conventional diesel (e.g. 1:4 ratio), it can still lead to a significant reduction in emissions.

3.2.2 Dry Extraction

The global sensitivity analysis and the variation of the GHG emission and EBR with the two most dominant parameters for the gasification-CHP route are illustrated in **Figure 7**. As can be seen in this figure, the dryer energy demand and algae oil content were almost equally important in determining the biodiesel carbon and energy footprints, while other factors had small or negligible effects. Expectedly, due to the high carbon and energy intensity of the drying step, both GHG emission and EBR values of biodiesel production from this route are rather high. The biodiesel produced via this strategy is likely to have a greater life cycle GHG emission than conventional diesel from crude oil, and even from the synthetic diesel produced via natural gas Fischer-Tropsch process (See Figure 4).

The global sensitivity analysis revealed that, for both strategies considered for the use of syngas generated from the gasification of dry extraction OEA, the algae oil content and the dryer energy demand were the dominant parameters. According to the results presented in Figure 7 for gasification-CHP (route 3), the sensitivity of GHG emission (and EBR) to the algae oil content is directly proportional to the dryer energy demand. In contrast, a larger variation in the well-to-wheel GHG emission (and EBR) with respect to the dryer energy demand were observed at lower algae oil contents. After all, the energy recovery from OEA via gasification-CHP would not be able to fully offset the energy demand of the algal biorefinery, adding a substantial carbon (and non-renewable energy) footprint to the biodiesel product. However, as no major breakthrough is required in this route, gasification-CHP conversion of OEA can help establish algal biorefineries and pave the way for more complex low carbon pathways.

The results of global sensitivity analysis concerning the conversion of OEA to synthetic diesel via gasification-FT is presented in **Figure 8**. As discussed earlier, although the energy content of OEA is not directly used within the biorefinery, this conversion strategy benefits from the highest algae-to-diesel yield, dampening the adverse environmental impacts per unit energy of the end product from the non-energy-related stressors. However, in spite of the slight reduction in the GHG emission of the non-energy-related factors, the extensive use of external fossil energy simply masked such gains and leads to increased overall emissions.

The LCA and global sensitivity results presented here, clearly indicate that, even under optimistic scenarios, the dry extraction routes would not be able to realise the environmental benefits of algae, and indeed they are likely to emit more greenhouse gases compared to petroleum-derived diesel. This finding is consistent with a previous LCA study in which the energy of OEA was assumed to be recovered using a biomass boiler [4].

3.2.3 Solar-Assisted Drying

The severe dependence of the GHG emission and EBR to the dryer energy demand in dry extraction routes suggests that a tremendous improvement with respect to these metrics can be achieved upon decarbonisation of the drying process. As discussed earlier, the implementation of solar energy is inherently a reasonable choice for such purposes. Although solar energy, in principle, can be applied for decarbonising heat and power demand of an algal biorefinery simultaneously, the analysis presented herein solely focuses on the direct use of solar thermal energy in biomass drying. To this end, it was assumed that using solar energy, the solid content of the feedstock after dewatering (i.e. 20 wt%) is increased from 26-36 wt%, corresponding to the removal of 1.15-2.22 kg water per kilogram of dry algae feedstock. The nominal value for the final concentration after solar drying (i.e. 31 wt%) was chosen in such way that the energy from the OEA unit can fully meet the demand of the entire biorefinery. Such arrangement would be achieved by using a part of the generated syngas solely for heating purposes, and the remaining part for the co-generation of heat and power in the CHP unit.

Despite the apparent economic and environmental advantages that brings to an algal biorefinery plant, the use of solar energy for drying of an oil-containing biomass should be treated with caution, primarily due to the vulnerability of the oil to degradation after being harvested and the limitations related to the drying rate and land area that is required for an extensive solar drying [5]. In our view, the assumption made in this study with regard to the extent to which the algae slurry is concentrated with the aid of solar energy represents a practical scenario.

The results obtained from global sensitivity analysis of the solar-assisted drying pathways incorporating a CHP unit and Fischer-Tropsch for the conversion of syngas are depicted in **Figures 9** and **10**, respectively. For the integrated gasification-CHP process (*route 5*), the dominant parameters include dryer energy demand and algae annual productivity, and surprisingly, the algae oil content was found to play a minor role. The variation in the GHG emission and EBR turned out to be rather limited over the entire range considered for the parameters (i.e. approximately 45-70 g e-CO_2/MJ_b and 0.7-0.9 MJ_f/MJ_b, respectively). These values are well below the carbon footprint and non-renewable energy

consumption of the conventional diesel, rendering the strategy one of the second most environmentally-benign pathway considered in this study after the scenario involved wet extraction and hydrothermal gasification (*route 2*).

According to the results shown in Figure 10, the algae oil content, dryer energy, grid carbon emission, and algae annual productivity have moderate impacts on the GHG emission of the algae-derived diesel produced from solar-assisted drying and gasification-FT process (route 6). The same parameters constituent the most important ones for the EBR of this route, except for the grid carbon footprint which is in this case replaced with pond water velocity. However, these parameters have relatively small impact on GHG and EBR values as shown in the same figure. The algae-derived diesel (i.e. sum of biodiesel from oil esterification and synthetic diesel from FT process) offers no marked advantage in terms of life cycle GHG emission and energy consumption over conventional diesel.

3.2.4 GHG Reduction Targets

As biofuels are gaining a more significant share in the transportation energy arena, sustainability issues such as GHG reduction, biodiversity, and land-use are receiving ever-increasing attention from legislators. As far as GHG reduction is concerned, each country has set out a threshold for the life cycle GHG emission of a biofuel produced from a certain type of feedstock (e.g. lignocellulosic, waste, sugarcane, etc.). These thresholds typically vary from 20 to 60 % of the emissions of the respective fossil-derived fuel (e.g. 91.7 g e-CO_2/MJ_b for diesel) and expected to increase in the future. For example, in the UK, the GHG reduction threshold that applies to the algae-derived biodiesel, albeit if the algae was not grown using wastewater, is currently set to 35%, and will increase to 50% in 2017, and finally to 60% in 2018 [19]. Similarly, the GHG reduction threshold related to algal biodiesel in the EU and USA are set at 60% [20] and 50% [21], respectively. It should be also noted that as more unconventional oil (e.g. tar sand) enters the fuel mix, the average GHG emission of the fossil diesel is likely to increase in the future, which in turn will improve the relative advantages of biofuels in general, and algal biodiesel in particular. In this part, we assess the potential of different algae conversion strategies to meet these targets. To this end, contours plots of GHG reduction potentials are generated by varying the two most influential parameters previously identified by global sensitivity analysis (**Figure 11**). Obviously, the analysis presented here is limited to the conversion routes that can possibly reduce emissions respective to conventional diesel (i.e. routes 1, 2, and 5). The analysis revealed that hydrothermal gasification, based on the assumption made in this study, is in fact the only conversion pathway that can meet the ultimate 60% GHG reduction targets. However, a process comprised of solar-assisted drying of algae and gasification-CHP conversion of OEA (route 5) also holds promise to bring significant emission savings, particulary if higher solid concentrations can be obtained from the solar drying process without degrading the algae oil and/or extending the drying time beyond a reasonable span. The maximum GHG reduction that anaerobic digestion (route 1) can offer is unlikely to exceed 30%, which itself can be achieved only at algae oil contents of greater than 30% and an extraction energy demand of smaller than 4 MJ/kg_{algae}.

4 Conclusions

The environmental impact of different biodiesel production strategies from algae feedstock in terms of greenhouse gas emission and non-renewable energy consumption were studied, and the results were subsequently benchmarked against those of conventional and synthetic diesel from fossil resources. The algae cultivation in open pond raceways and the transesterification process for the conversion of algae oil into biodiesel constitute the common elements among all considered scenarios. Anaerobic digestion and hydrothermal gasification were considered for the conversion of the residues from the wet oil extraction process; while integrated gasification-heat and power generation and gasification-Fischer Tropsch processes were considered for the conversion of the residues from the dry oil extraction process. The GHG emission per unit energy of the biodiesel at nominal values for the process parameters were found to be as follows, hydrothermal gasification: 41 g e-CO_2/MJ_b, anaerobic digestion: 86 g e-CO_2/MJ_b, gasification-CHP: 109 g e-CO_2/MJ_b, and gasification-Fischer Tropsch 124 g e-CO_2/MJ_b. If solar energy is utilised to increase the biomass concentration from 20 to 31 wt%, the GHG emission of the algae-derived diesel from gasification-CHP and gasification-Fischer Tropsch is reduced to 59 and 87 g e-CO_2/MJ_b, respectively. In general, the non-renewable energy consumption ratios were closely correlated to the GHG values: hydrothermal gasification 0.50 MJ_f/MJ_b), anaerobic digestion: 0.96 MJ_f/MJ_b, gasification-CHP: 1.48, gasification-FT: 1.81. In the case of solar-assisted drying processes, the EBR values were calculated at 0.76 and 1.24 MJ_f/MJ_b for gasification-CHP and gasification-FT processes, respectively. Using the High Dimensional Model Representation (HDMR) method, a global sensitivity analysis has been performed to rank the input parameters with respect to their influence on key sustainability metrics. It was found that, considering reasonable ranges over which each parameter can vary, the most influential input parameters for the wet extraction route include the extractor energy demand, and the yield of the methane generated from anaerobic digestion or hydrothermal gasification of the oil extracted-algae. The important input parameters for the dry extraction route include the algae oil content, the dryer energy demand, and the algae annual productivity. The results imply that algal biodiesel production from a dried feedstock may only prove sustainable if a low carbon solution such as solar drying is implemented to reduce the water content of the feedstock. Furthermore, the analysis revealed that hydrothermal gasification of oil-extracted algae, based on the assumption made in this study, is in fact the only conversion pathway that can meet the ultimate 60% GHG reduction targets compared to conventional diesel. However, a process comprised of solar-assisted drying of algae and gasification-CHP for the conversion of OEA also holds promise to bring significant emission savings, particulary if higher solid concentrations can be obtained from the solar drying process. In summary, algal biodiesel production from both wet extraction and solar-assisted drying routes are environmentally viable and policies and incentives should ideally support research, development, and commercialisation for both of these routes.

Acknowledgements

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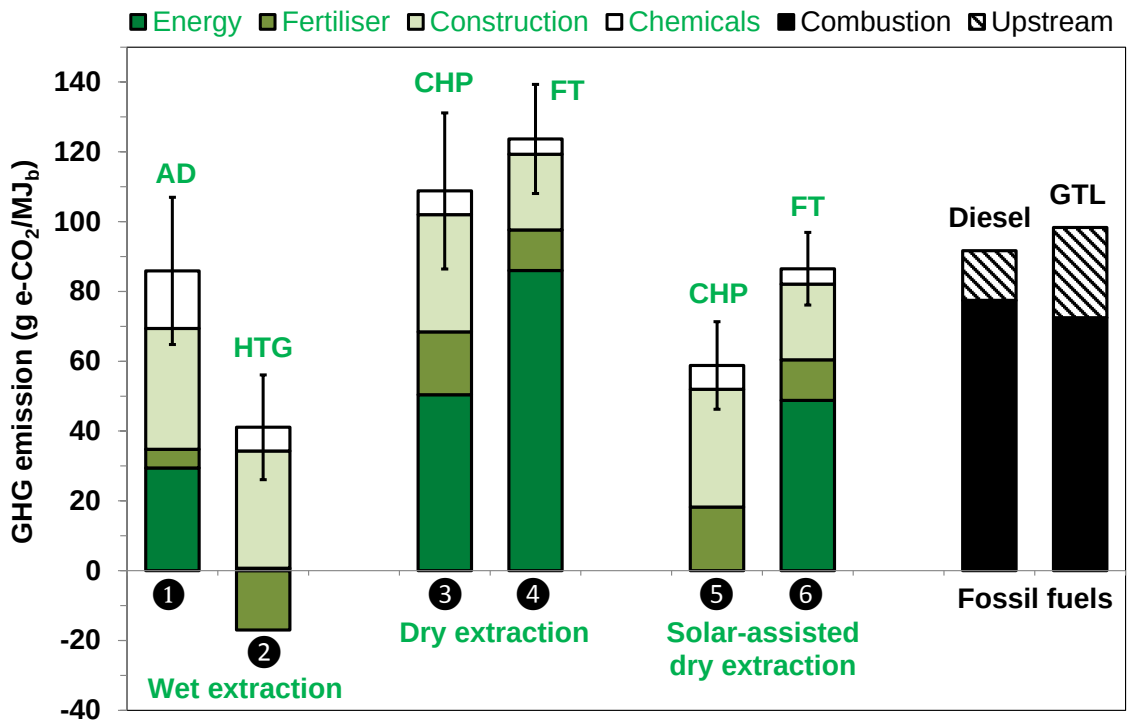
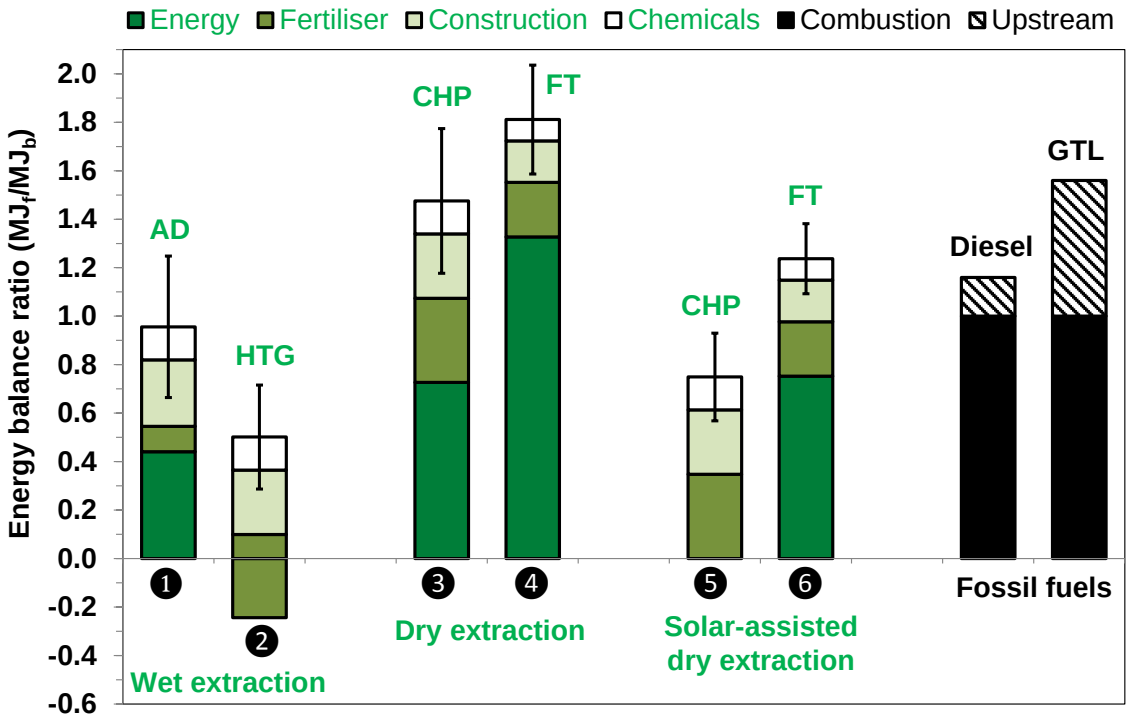
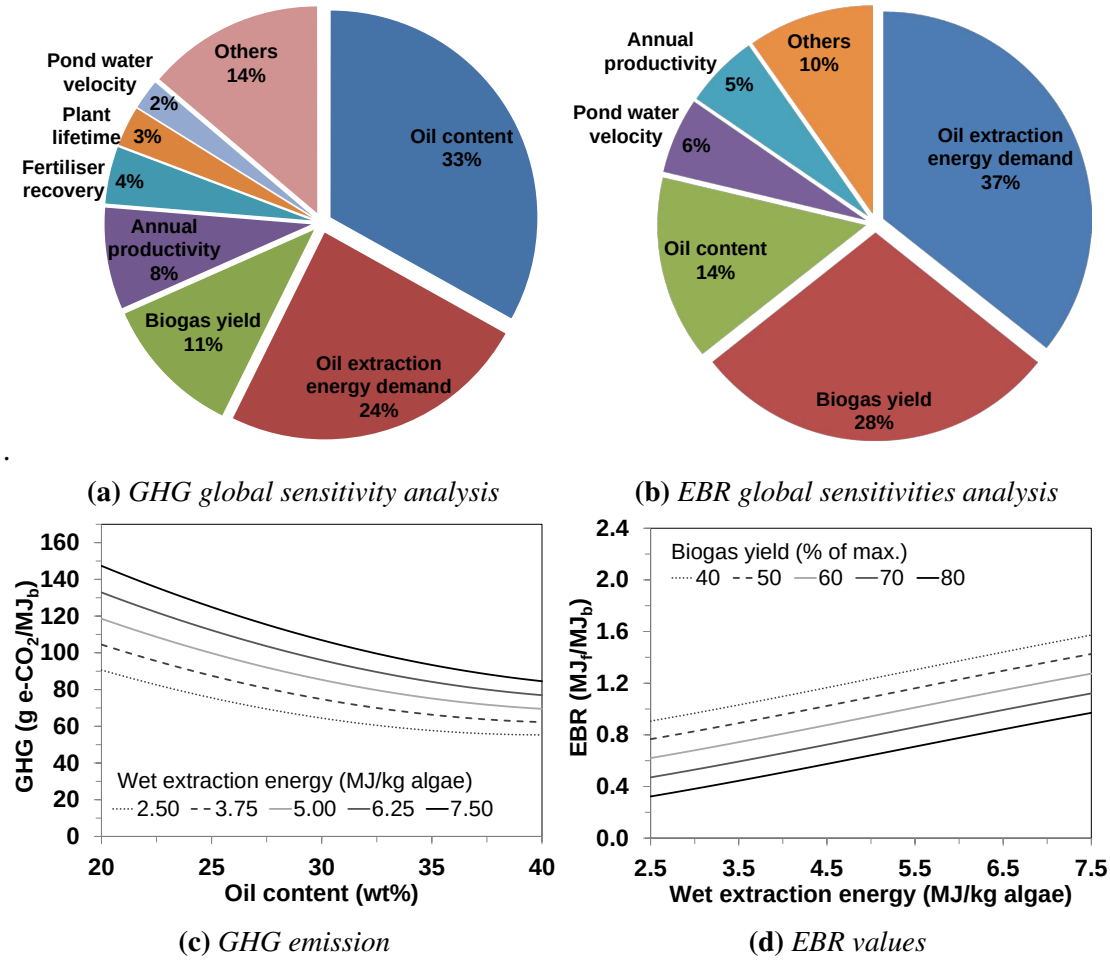


(a)



(b)

Figure 4: *Baseline values for GHG emission (a), and energy balance ratio (b) of biodiesel produced from the processes considered in this study. The corresponding values for petroleum diesel and FT diesel from natural gas (GTL) are included for comparison.*



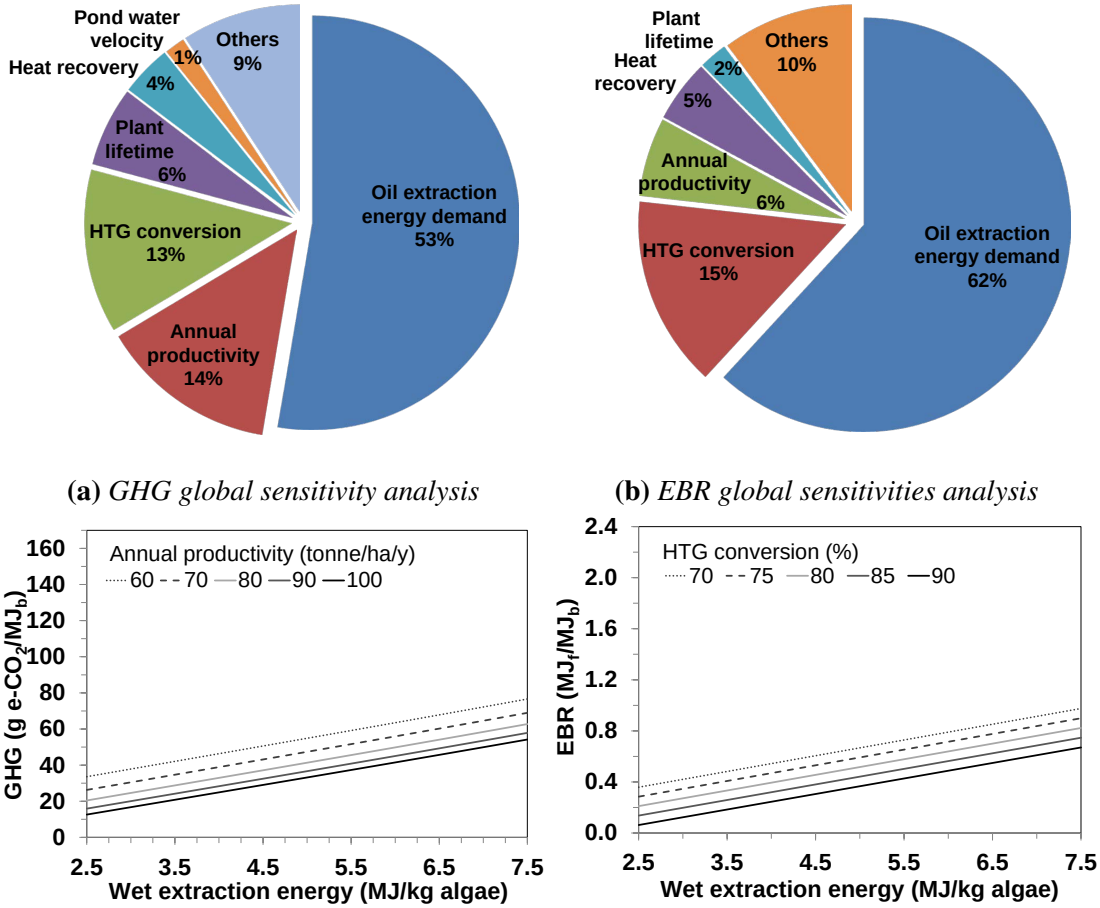
(a) *GHG global sensitivity analysis*

(b) *EBR global sensitivities analysis*

(c) *GHG emission*

(d) *EBR values*

Figure 5: *Global sensitivity analysis for GHG (a), and EBR (b); and effects of the two most influencing parameters on GHG (c) and EBR (d) for biodiesel production from wet extraction and anaerobic digestion (AD) (route 1).*



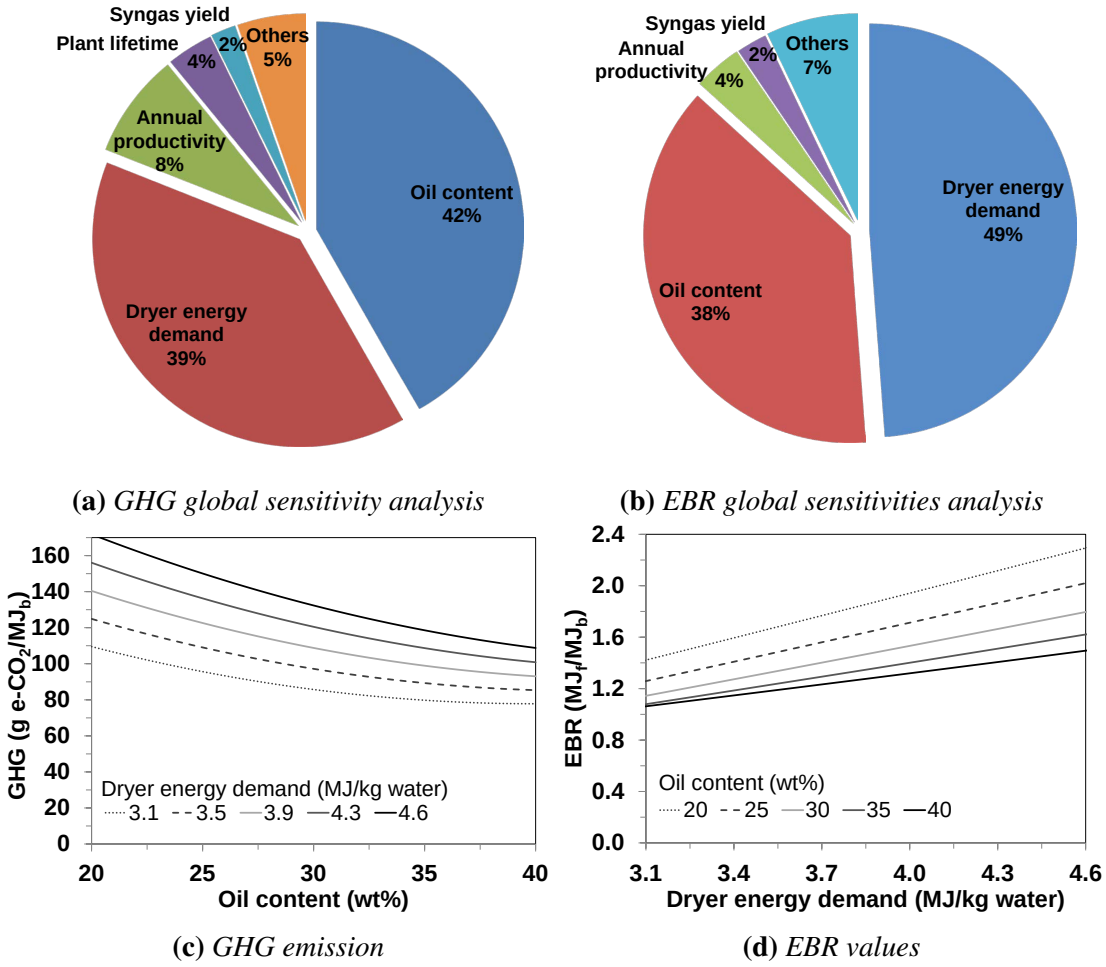
(a) *GHG global sensitivity analysis*

(b) *EBR global sensitivities analysis*

(c) *GHG emission*

(d) *EBR values*

Figure 6: *Global sensitivity analysis for GHG (a), and EBR (b); and effects of the two most influencing parameters on GHG (c) and EBR (d) for the wet extraction and hydrothermal gasification (HTG) (route 2).*



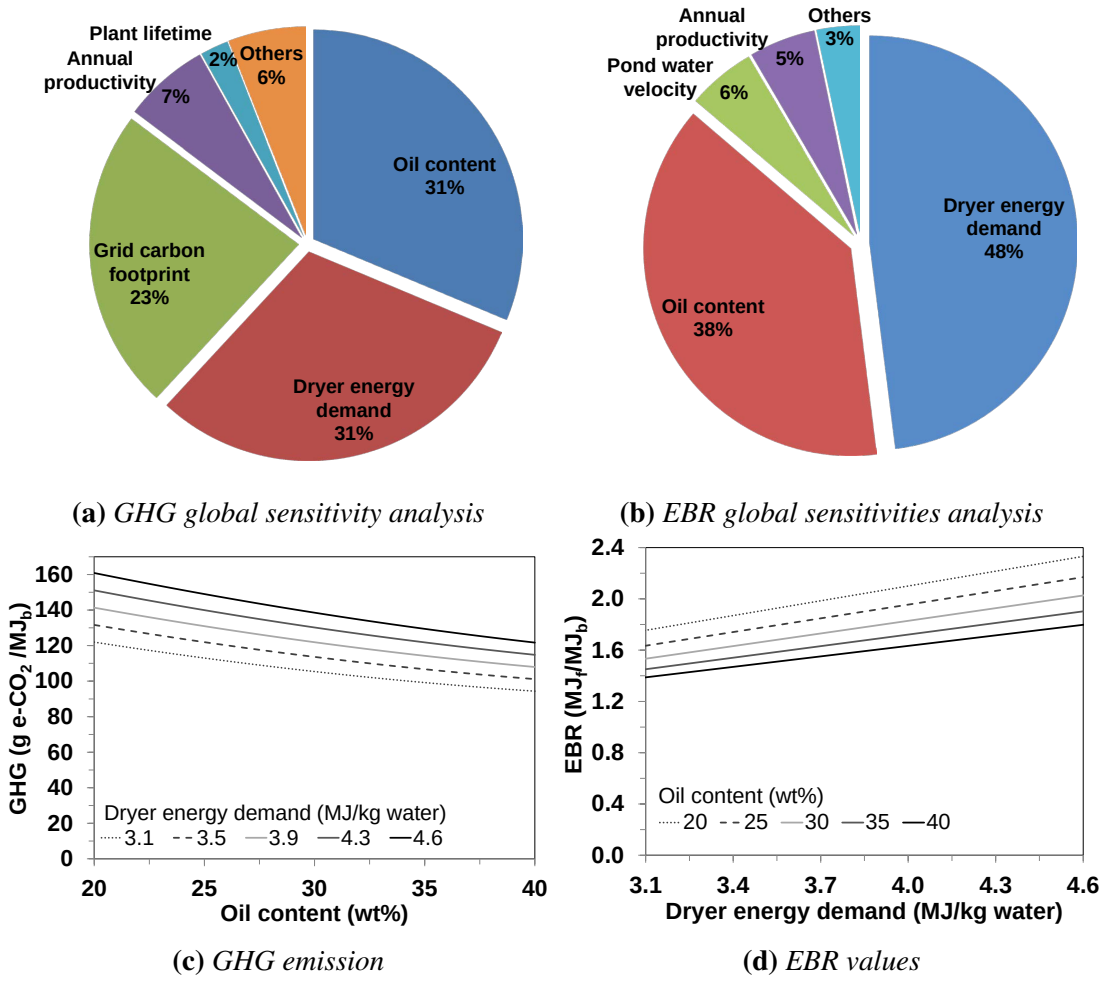
(a) *GHG global sensitivity analysis*

(b) *EBR global sensitivities analysis*

(c) *GHG emission*

(d) *EBR values*

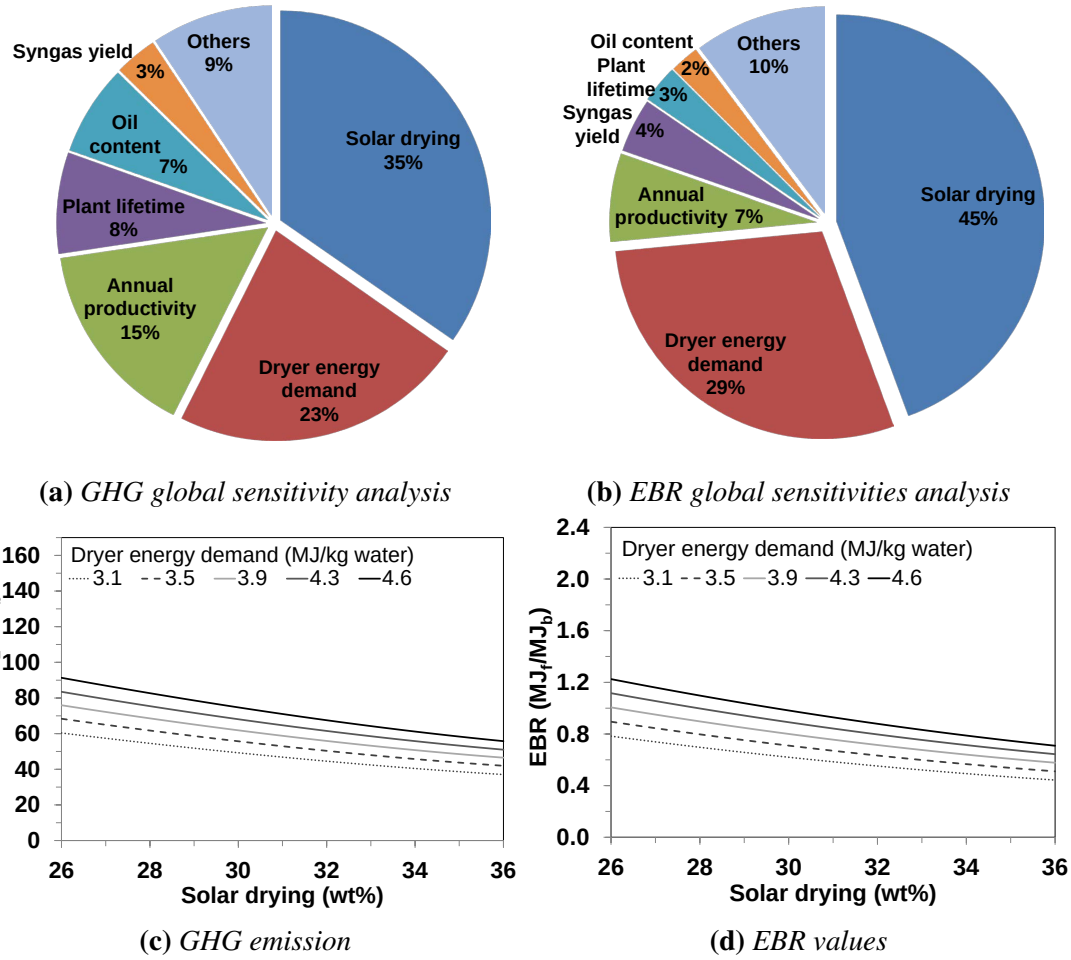
Figure 7: *Global sensitivity analysis for GHG (a), and EBR (b); and effects of the two most influencing parameters on GHG (c) and EBR (d) for dry extraction and integrated gasification-CHP (route 3).*



(a) *GHG global sensitivity analysis* **(b)** *EBR global sensitivities analysis*

(c) *GHG emission* **(d)** *EBR values*

Figure 8: *Global sensitivity analysis for GHG (a), and EBR (b); and effects of the two most influencing parameters on GHG (c) and EBR (d) for dry extraction and integrated gasification-FT (route 4).*



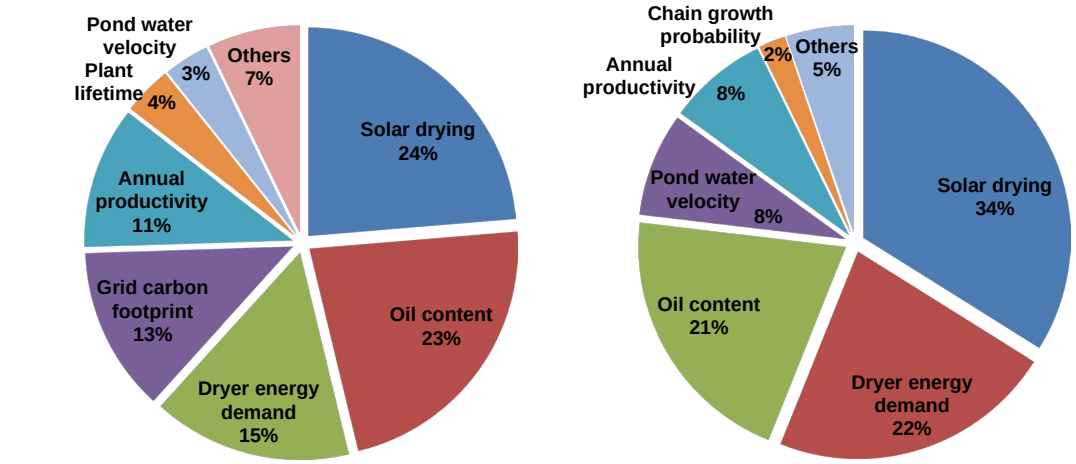
(a) *GHG global sensitivity analysis*

(b) *EBR global sensitivities analysis*

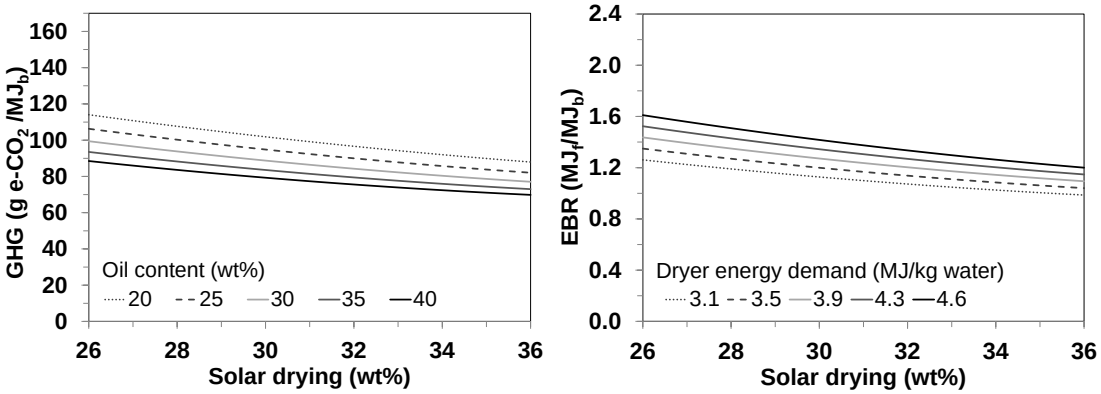
(c) *GHG emission*

(d) *EBR values*

Figure 9: *Global sensitivity analysis for GHG (a), and EBR (b); and effects of the two most influencing parameters on GHG (c) and EBR (d) for solar-assisted dry extraction and integrated gasification-CHP (route 5).*

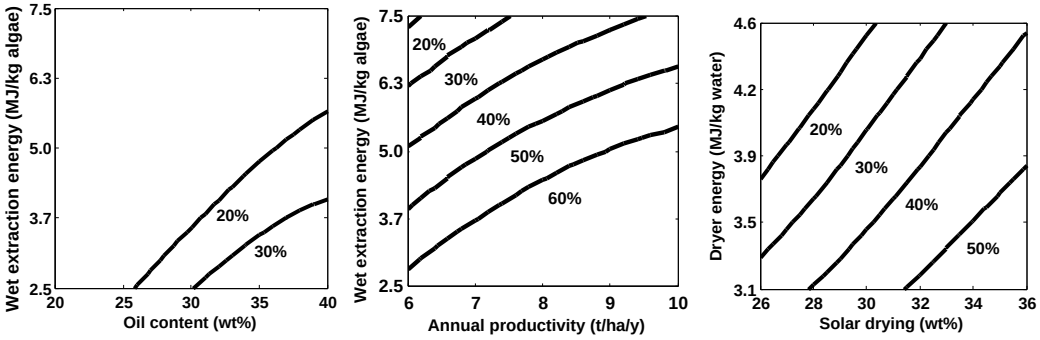


(a) *GHG global sensitivity analysis* **(b)** *EBR global sensitivities analysis*



(c) *GHG emission* **(d)** *EBR values*

Figure 10: *Global sensitivity analysis for GHG (a), and EBR (b); and effects of the two most influencing parameters on GHG (c) and EBR (d) for solar-assisted dry extraction and integrated gasification-FT (route 6).*



(a) *AD (route 1)* **(b)** *HTG (route 2)* **(c)** *Solar-assisted IGCHP (route 5)*

Figure 11: *Contour plots of algal biodiesel GHG reduction produced via different conversion strategies with respect to the emissions from fossil diesel.*

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5 Supplementary Information

Table S.1: *Embedded greenhouse gas emission and fossil energy consumption.*

	GHG	Unit	Energy	Unit	Reference
Construction					
Concrete	0.13	kg e$-CO_2$/kg	0.67	MJ/kg	[22]
Stainless steel	2.00	kg e$-CO_2$/kg	21.6	MJ/kg	[23]
PVC	2.50	kg e$-CO_2$/kg	67.5	MJ/kg	[4]
Fiberglass	1.53	kg e$-CO_2$/kg	28.0	MJ/kg	[4]
Fertilizer					
Ammonia	1.69	kg e$-CO_2$/kg	32.7	MJ/kg	[24, 25]
Single superphosphate	0.22	kg e$-CO_2$/kg	3.2	MJ/kg	[25, 26]
Electricity					
France	0.030	kg e$-CO_2$/MJe	3.63	MJ/MJe	[15]
USA	0.225	kg e$-CO_2$/MJe	3.77	MJ/MJe	[15]
China	0.342	kg e$-CO_2$/MJe	3.25	MJ/MJe	[15]
Chemicals					
Methanol	1.86	kg e$-CO_2$/kg	36.5	MJ/kg	[4, 24]
Hexane	3.61	kg e$-CO_2$/kg	52.6	MJ/kg	[1]
Fossil Fuels (LHV basis)					
Natural gas	44.85	MJ/kg (LHV)			
Upstream	0.0210	kg e$-CO_2$/MJ			[27]
Combustion	0.0553	kg e$-CO_2$/MJ			[27]
Total	0.0763	kg e$-CO_2$/MJ	1.10	MJ/MJ	[27, 28]
CNG	44.85	MJ/kg (LHV)			
Upstream	0.0262	kg e$-CO_2$/MJ			[27, 28]
Combustion	0.0553	kg e$-CO_2$/MJ			[27]
Total	0.0815	kg e$-CO_2$/MJ	1.18	MJ/MJ	[27, 28]
Conventional diesel	41.84	MJ/kg (LHV)			
Upstream	0.0142	kg e$-CO_2$/MJ			[29]
Combustion	0.0775	kg e$-CO_2$/MJ			[29]
Total	0.0916	kg e$-CO_2$/MJ	1.16	MJ/MJ	[29]
FT diesel	44.01	MJ/kg (LHV)			
Upstream	0.0258	kg e$-CO_2$/MJ			[29]
Combustion	0.0725	kg e$-CO_2$/MJ			[29]
Total	0.0983	kg e$-CO_2$/MJ	1.56	MJ/MJ	[29]
Transportation	0.055	kg CO_2/t/km	0.67	MJ/t/km	[27]
Hydrogen from SMR	0.0982	kg e$-CO_2$/MJ	1.51	MJ/MJ	[30]

1 Estimated based on chemical formula and conversion efficiency of 0.85% from primary fossil fuel

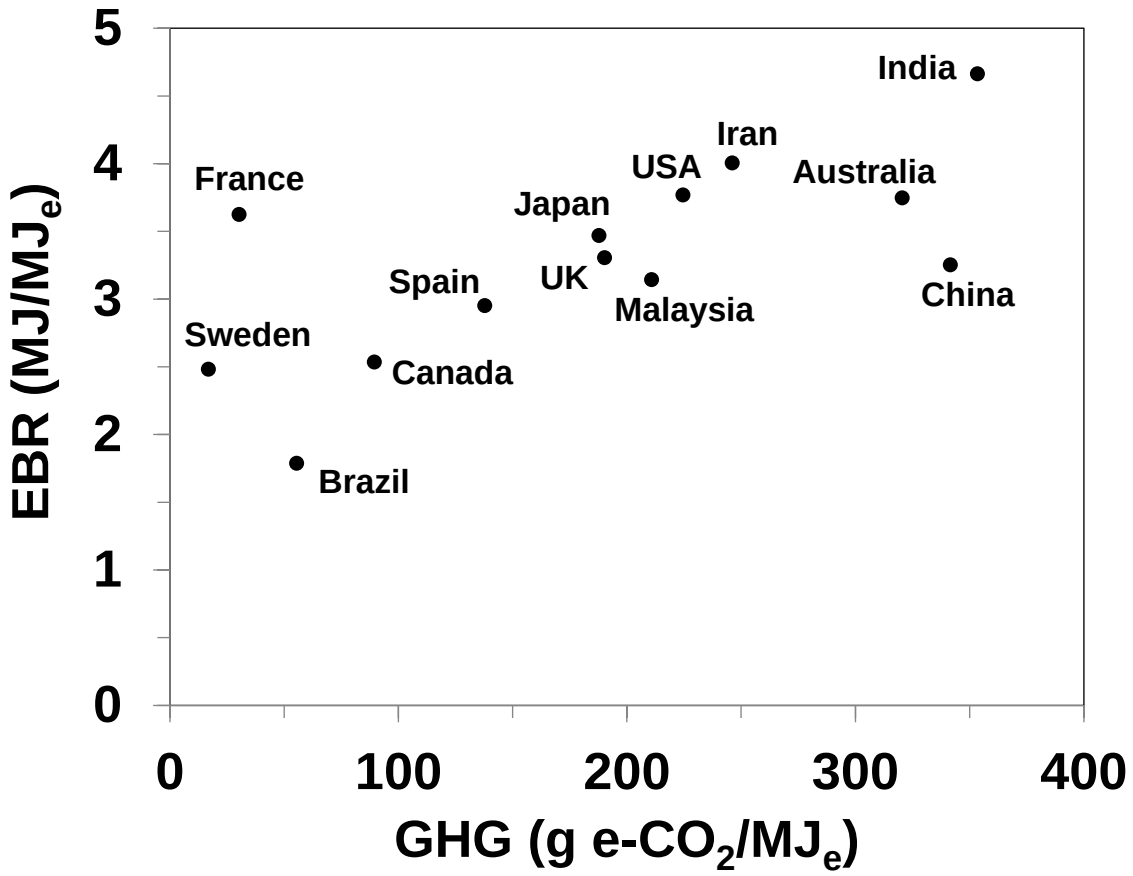

Figure S.1: *Energy balance ratio (i.e. non-renewable energy consumption to generate 1 MJ electricity) vs. GHG emission of low voltage electricity mixes in 2008 [15].*

Table S.2: *Microalgae biochemical fractions, elemental composition, and heating value [6].*

Fraction	Weight(%)	Elemental composition	LHV (MJ/kg)
Lipid	20-40	$C_1H_{1.83}O_{0.17}N_{0.0031}P_{0.006}$	36.3
Protein	37-50	$C_1H_{1.56}O_{0.3}N_{0.26}S_{0.006}$	23.9
Carbohydrate	18-25	$C_1H_{1.67}O_{0.83}$	17.3
Nucleic acids	5	$C_1H_{1.23}O_{0.74}N_{0.40}P_{0.11}$	14.8

Table S.3: *Fixed model parameters for microalgae cultivation and harvesting.*

Algae cultivation					
Open pond			Paddlewheel		
Area	1	ha	Pump and gear steel	100	kg
Length	330	m	Impeller fiberglass	500	kg
Height	0.5	m	Manning's roughness	0.015	
Wet height	0.3	m	Efficiency	50	%
Thickness	0.15	m			
Concrete	4350	t	Pumping to clarifier		
			Horizontal distance	50	m
Nutrients			Elevation	1	m
CO_2	2.0	kg/kg_{algae}	Pipe roughness	1.5	μm
CO_2 blower	0.08	MJ_e/kg	Pump efficiency	50	%
Ammonia	1.8	kg/kg N	Power	0.226	MJ_e/kg_{algae}
SSP	19	kg/kg P	Efficiency	50	%
Losses	5.0	%	Weight	200	kg steel
Harvesting					
Clarifier			Thickener		
Design basis	160	t algae/y	Retention time	10	h
Retention time	6	h	Num. of tanks	1	
Diameter	2.6	m	Spare tank	1	
Height	10.4	m	Total volume	44	m^3
Num. of tanks	5		Concrete	50	t
Spare tank	1		Output concentration	50	kg/m^3
Total volume	315	m^3	Separation efficiency	95	%
Concrete	710	t			
Output conc.	20	kg/m^3	Centrifuge		
Separation efficiency	95	%	Output concentration	200	kg/m^3
			Power	3.6	MJ_e/m^3
Others					
Piping			Transportation		
PVC	7000	kg	Average distance	50	km

Table S.4: *Fixed model parameters for algae drying, oil extraction and esterification steps.*

Algae drying	Conventional	Solar-assisted	
Design basis	160	160	t algae/y
Feed concentration	20	26-36	wt%
Output concentration	90	90	wt&
Water evaporation	3.9	1.7-2.7	kg/kg_{algae}
Dryer web area	80	80	$m^2/kg_{evap.}$.s
Concrete	1100	600	kg/ha
Steel	1000	800	kg/ha
Oil extraction	Wet extraction	Dry extraction	
Feed concentration	20	90	wt%
Extraction efficiency	95	95	%
Solvent loss	0.005	0.005	kg/kg_{oil}
Oil esterification			
Biodiesel yield	0.97	kg/kg_{oil}	
Glycerol yield	0.10	$kg/kg_{biodiesel}$	
Methanol consumption	0.11	kg/kg_{oil}	

Table S.5: *Fixed model parameters for the conversion of wet extraction residue.*

Anaerobic digestion (AD)					
Maximum methane yield			Digester tanks		
Oil [9]	41.8	mol/kg	Design basis	160	t algae/y
Protein [9]	18.4	mol/kg	Conc.	120-160	kg/m^3
Carbohydrate [9]	17.1	mol/kg	Ret. time	30	d
Nucleic acids	11.4	mol/kg	Diameter	3.2	m
Glycerol	18.4	mol/kg	Height	3.2	m
			Tanks	4	
Feed VS/TS	0.9		Total vol.	77	m^3
Biogas CH_4/CO_2	2.3	mol/mol	Concrete	173	t
			Liner thick.	0.005	m
Energy demand			Liner weight	578	kg
Mixing	0.26	MJ$_e$/kg$_{feed}$			
Heat	2.5	MJ/kg$_{feed}$	Digestate solid		
Centrifuge	3.6	MJ$_e$/m^3	Solid content	30	wt%
Gas cleanup	0.9	MJ$_e$/m^3	Carbon in solid	50	%
			N_2O emission	1.0	wt% of N
Hydrothermal gasification (HTG)					
Maximum gas yields			Hydrothermal gasifier		
Methane	22.9	mol/kg	Temperature	400	°C
Hydrogen	1.27	mol/kg	Pressure	250	bar
Ammonia	0.13	mol/kg	Conc.	120-160	kg/m^3
Carbon dioxide	18.1	mol/kg	WHSV	10	h^{-1}
Carbon monoxide	0.02	mol/kg	Ru/support	5	wt%
Nitrogen	0.13	mol/kg	Bed porosity	40	%
			Pretreatment		
Feed LHV	20.9	MJ/kg$_{dry}$	Residence time	1	h
Product LHV	18.6	MJ/kg$_{gas}$	Separators		
			First	250	bar
Energy demand			Second	2	bar
Pump	0.40	MJ$_e$/kg$_{algae}$			
			Total weight	1900	kg steel
Combined heat & power (CHP)					
Scale for 1 ha algae farm			Efficiency		
AD	13.7	kW	Thermal	51	% LHV
HTG	14.0	kW	Electrical	34	% LHV

Table S.6: *Fixed model parameters for the conversion of dry extraction residue.*

Gasification [12]					
Feedstock moisture	10	wt%	Syngas composition		
Feedstock LHV	20.9	MJ/kg	H_2	40	%
Gasifier temp.	800	°C	CO	25	%
Syngas temp after HX	140	°C	CO_2	20	%
Syngas after scrubber	40	°C	CH_4	10	%
Air preheating	500	°C	LHV	12.4	MJ/kg
Steam to fuel ratio	0.5	kg/kg			
Combined heat & power (CHP)			Conventional	Solar-assisted	
Capacity			31.5	31.5	kW
Elec. eff.			20	15	% LHV
Thermal eff			68	72	% LHV
Inlet temp.			40	40	°C
Fischer-Tropsch (FT) [14]					
Inlet temp.	200	°C	C_{5+} yield		
Outlet temp.	240		$\alpha = 0.80$	74	%
Pressure	40	bar	$\alpha = 0.85$	84	%
Surplus FT steam [1]			$\alpha = 0.90$	91	%
Temp.	230	°C	Conversion		
Pressure	12	bar	Per pass	40	%
Amount	0.042	MJ/MJ_{feed}	Overall	100	%

1 Estimated based on the heat demand for drying of feedstock in [14]