Impacts of the contradictory factors in algal CO2 sequestration with sustainable biofuel benefit

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Research

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Abstract

Background The purpose would discover the impacts of the contradictory factors in application of algae in CO_2 sequestration with sustainable biofuel benefit. The quantitively assessment model and approach have been established coupling upstream CO_2 source and deliverables with downstream algal biofuel deliverables at the uniform algae level of *Nannochloropsis oceanica*, which would be benefit for algae biofuel deliverables choice. The functional units have been defined at energy consumption (MJ) per final mass product (algae, jet biofuels by three refining pathways, biodiesels by three refining pathways) and energy consumption (MJ) per final energy yield (algae, jet biofuels, biodiesels). Computational framework is classified into three sub-models, including CO_2 source and deliverable model, algae cultivation and deliverable model, refining process and biofuel deliverable model. This life cycle assessment investigated the following impacts: transportation distances and purification modes with flue gas CO_2 concentrations, lipid content with specific productivity and CO_2 biofixation coupling the nutrient supply, final products including algae, jet biofuel and biodiesel.

Results Coupling the influence of transportation distances and purification modes on the energy consumption, flue gas with a wide range of CO_2 concentration was compared for two type deliverables including algal CO_2, edible CO_2. flue gas with low CO_2 concentration is appropriate for on-site algal CO_2 deliverable within 10km while flue gas with above 95% CO_2 is flexible to transportation distance and appropriate for edible CO_2 deliverable. Specific productivities and CO_2 fixation both comply with negatively logarithmic relationship with lipid contents. Coupling the effects of algae specific productivity and CO_2 evaporation loss, the total CO_2 fixation efficiencies were investigated above 90% at below 28 % lipid but obviously decrease at above 40% lipid. The nutrient supply enhances specific productivity and protein content but with indirect energy consumption. The total energy consumptions of different target products with upstream CO_2 source and algae to downstream biofuel were calculated quantitatively on edible algae and general algae.

Conclusions Biodiesel_{wet} and HTL-HRJ jet biofuel performed the priorities in energy consumption. Lipid content and profile defined biofuel deliverables in quantity and quality. The LCA indicated that allocation is a crucial issue to balance energy, environment and economy decision on target product choice and by-products. Coupling solar energy utilization and by-product of bioactive nutrients effects, the positive energy gains have been investigated at a wide range of lipid contents despite of jet biofuel or biodiesel. The results would enhance the interests in both LCA and application of algae in CO_2 sequestration with sustainable biofuel benefit.

1. Background

The climate change, arising mainly from flue gas emission derived from coal power industries, is currently a critical environmental issue. Considering the electricity demands and subsequent emissions, CO_2 algae-fixation are becoming an attractive approach for CO_2 capture and additional benefits in downstream algae utilization due to the priorities of environmental approval and sustainable potential. Flue gas derived from a coal-power station is an ideal carbon source for the large-scale culture of algae due to the stable and centralized emission features [1], which have been qualified as the carrier of bioenergy with bio-nutrient benefit in conjunction with CO_2 mitigation[2, 3]. However, algae chain should balance economy, energy, and environment issue for target product choice. Flue gas purification enhancement for edible bio-nutrient leads to high energy consumption despite economy benefit. Moreover, the ideal algal species should be qualified with the properties of fast growth and high content of lipids, but algae growth rate decreases obviously with the increase of lipid content, and the increase of algae growth rate is benefit for CO_2 fixation while the increase of lipid content in algae is benefit for biofuel in quality and quantity.

Most reviews[4–8] provide the most promising microalgae species for different types of biofuel. Species of Nannochloropsis oceanica is considered as an ideal algal species by characterized with rapid growth and high lipid content [9]. The challenge of the tolerance of high CO_2 concentration has been overcome by gradually increasing CO_2 concentration to even purified CO_2 by coupling the pH control and aeration control. The pollutants in flue gas have been proved to the tolerance of SO_X less than 60 ppm, NO_2 less than 300 ppm, and NO less than 60 ppm but special trace metal have been investigated aggregation in algae cell. For edible algae, flue gas must further be purified as edible CO_2 source to remove trace metals for inhibiting trace metal in bio-nutrient. Subsequently, edible CO_2 requirement enhances in energy consumption but benefit in economy while general algae feedstock lose advantage without edible bionutrient benefit despite enhancement in CO_2 sequestration. The available algae cultivation to target appropriate algal product should also be balanced between energy consumption and economy related with algae product in quality and quantity.

Algae industry is currently trying to achieve a broad range of products, from bio-nutrient[10–12] and animal feed[13, 14], to jet biofuels[15, 16] and biodiesel[17–19]. However, as the complex long value chains and uncertainty in upstream algae feedstock to downstream bioenergy conversion systems, it is difficult to reasonably deduce the available algal final product with upstream flue gas source and appropriate algae cultivation. LCAs[20–26] have been undertaken aiming to assess products and processed based on available models and approaches. The current results of the assessment are complex due to lack of the discussion of complicated relevance system from upstream CO_2 source to downstream consequences product.

In this study, quantitively assessment model and approach have been established and investigated coupling CO_2 deliverables and algal biofuel deliverables at the uniform level of Nannochloropsis oceanica. Especially, in comparison with refining process and by-product impacts, mass allocation and energy allocation were involved in the models in compliance with not only upstream requirement but also downstream consequences. The results would enhance the interests in both LCA and application of algae in CO_2 sequestration with sustainable biofuel benefit.

2. Results And Discussion

2.1 CO_2 source to edible and non-edible deliverables

CO_2 deliverables as the upstream of algae deliverables should comply with both requirement of algae growth and transportation distance. Flue gases normally comprises of CO_2 in the range of 95% – 98% derived from coal chemical industries while flue gas is in the range of 12%-15%with CO, NO_X, SO_X, heavy metal derived from coal power station. Considering general algae cultivation requirement, CO_2 deliverables should achieve $SO_X \leq 60$ ppm, $NO_2 \leq 300$ ppm, and NO ≤ 60 ppm but with a wide range of CO_2 concentration. Considering edible algae for bionutrient benefit, CO_2 deliverables should achieve edible requirement with CO_2 above 99.98%.

Despite flue gas concentration and energy consumption, only cryogenic fractionation can comply with edible algae growth requirement. For flue gas at 15% CO_2 as source, membrane fractionation can achieve general growth requirement with the lowest energy consumption. Flue gas with above 95% CO_2 as source, chemical absorption and cryogenic fractionation can available for general growth requirement.

CO_2 concentration and purity after capture and purification are crucial for the choice of CO_2 transportation modes. CO_2 transportation for long distance is usually carried out in liquid phase with above 95% CO_2 for a stable single-phase and less volume. The choice of appropriate mode of transportation depends on volume loads as well as transportation distance. For subsequent CO_2 distribution in bioreactor, energy consumptions are related with the depth of bioreactor, which usually are controlled at 0.25 m due to photosynthetic restriction. Coupling purification, transportation and distribution, the effects of transportation distance on energy consumption from CO_2 source to CO_2 deliverable are given in Fig. 1.

For flue gas at 15% CO_2, membrane separation takes the advantages in the lowest energy consumption within 30 km transportation distance by pipeline, given in Fig. 2(a), which indicated that flue gas should be used within 30 km. subsequently, the main energy consumption from CO_2 source to CO_2 deliverable are in the process of capture and purification with above 70% and about 20% in distribution in raceway pond and 10% in transportation. For above 30 km transportation distance, cryogenics purification with truck transportation takes obvious advantage above 40 km, shown in Fig. 2 (a). For flue gas at 95% CO_2, chemical adsorption with pipeline transportation within10km performs the lowest energy consumption while cryogenic fractionation with truck transportation at 20 km perform the lowest energy consumption, shown in Fig. 2 (b). Coupling the transportation distance and purification modes, flue gas with low CO_2 concentration is appropriate for on-site utilization within 10 km while flue gas with above 95% CO_2 is flexible to transportation distance and appropriate for edible CO_2 deliverable.

2.2 Algae cultivation for edible algae and algal biofuel carrier

Specific productivity and lipid content are crucial parameters related with Nannochloropsis deliverables in quality and quantity. Lipid content is related with bioenergy carrier and specific productivity is related with algae growth rate. For quantitively and qualitatively assessment on algae deliverable coupling the upstream CO_2 deliverable and downstream biofuel, the quantitative relationship of lipid content with specific productivity and CO_2 biofixation, are established based on lipid contents in the range of 12.6%–47.4%, shown in Fig. 2(a).

The carbon content of Nannochloropsis are calculated based on the lipid $C_{40}H_{74}O_5$(634), protein $C_{4.43}H_7O_{1.44}N_{1.16}$(100.1), and carbohydrate $C_6H_{12}O_6$(180) content with 8% ash [27]. According to the statistics, specific productivities decrease with the increase of lipid contents in compliance with logarithmic relationship, given in equation [1]. Although carbon abundant in algae increases linearly with the rise of lipid content, given in equation [3], CO_2 fixation decrease logarithmically with the rise of lipid content, given in equation [2]. Specific productivities and CO_2 fixation both comply with negatively logarithmic relationship with lipid contents.

Specific productivities ($g/m^2.d$) = – 10.89 ln (lipid %) + 44.025 $R^2 = 0.8812$ [1]

CO_2 fixation ($g/m^2.d$) = – 18.58ln (lipid %) + 76.518 $R^2 = 0.8595$ [2]

Carbon content (wt, %) = 0.0028 lipid (%) + 0.4486 $R^2 = 0.8831$ [3]

CO_2 fixation ($g/m^2.d$) = 1.7217 specific productivities ($g/m^2.d$) + 1.234 $R^2 = 0.9922$ [4]

CO_2 fixation efficiency (%) = 12.033 ln (Algae yield ($g/m^2.d$) + 64.567 $R^2 = 0.9112$ [5]

According to statistics results, the lipid productivities conducted similar at 2.25–2.56 $g/m^2.d$ in the wide range of specific productivities and lipid contents, shown in Fig. 3(a). CO_2 absorption efficiency in raceway pond was related with algae specific productivities, shown in Fig. 3(b). CO_2 fixation increase only lineally with algae specific productivities. It is investigated that CO_2 evaporation loss is 1.234 $g/m^2.d$ in raceway pond in spite of algae growth, given in equation [4]. Coupling the effects of algae specific productivity and CO_2 evaporation loss, the total CO_2 fixation efficiencies were investigated above 90% at below 28% lipid content and 80–90% at 28% – 36% lipid content, but obviously decrease at above 40% lipid content.

Coupling the influence of specific productivity with lipid content and CO_2 fixation, the lowest energy consumption per algae yield is at specific productivity 10.6 $g/m^2.d$ with lipid 24.3% while the lowest energy consumption per algae lipid yield is at specific productivity 5.2 $g/m^2.d$ with lipid 36.1%. Lipid content usually can be controlled by N nutrient supplement mode and algae growth cycle. The nutrient supply enhances specific productivity and protein content, but the nutrient supplement results in indirect energy consumption derived from nutrient product, which further increase the high content in carbohydrate with low lipid content. Therefore, specific productivity with lipid content could be controlled by nutrient supply for reduction of energy consumption and available feedstock for downstream biofuel.

2.3 Refining process for jet biofuel and biodiesel

Nannochloropsis (22.4% lipid, 9.22% protein, 60.4% carbohydrate and 8% ash), derived from practical flue gas cultivation in China, is considered as a feedstock to evaluate the energy consumptions on different biofuel deliverables by different refining process. The energy consumption based on product mass weight yield (MJ/kg product) are given in Fig. 3(a) while the energy consumption based on product energy yield (MJ/MJ product) are given in Fig. 3(b) at a uniform level of same algae.

Algae powder (19.4 MJ/kg) cost energy consumptions 21.7 MJ/kg and 1.12 MJ/MJ in press and dry process, which indicated that algae are unsuitable directly considering as the carrier of bioenergy due to negative energy yield. However, the thermal heat occupies around 50% in algae powder stage, which indicates that the potential reduction of energy consumption can be improved by utilization of waste heat or solar thermal heat.

In three refining processes for jet biofuel, HTL-HRJ performed the lowest energy consumption, and HRJ_{wet} conducted 1.5 times and HRJ_{dry} jet biofuel conducted 5.5 times than HTL-HRJ. The energy yield of HTL-HRJ and HRJ_{wet} process can achieve positive except HRJ_{dry} process. The hydrogen utilization is the main energy consumption in HTL-HRJ processes with about 50% in total energy consumption. The electricity utilization is the main energy consumption in $HRJ_{wet,}$ process with around 40% while the thermal heat is the main energy consumption in HRJ_{dry} process with around 80%.

In three pathways for algal diesel, $Biodiesel_{wet}$ process conducted the lowest energy consumption while $Biodiesel_{dry}$ conducted about 4 times and $Biodiesel_{RD}$ conducted 1.2 times. $Biodiesel_{dry}$ process performed negative energy gain as HRJ_{dry} process. $Biodiesel_{wet}$ process and $Biodiesel_{RD}$ can both achieve positive energy gain.

Coupling refining process and biofuel product, energy yield per energy consumption in refining fuel stage is lower than 1, which clearly implies an energy gain during the refining process. HTL-HRJ and HRJ_{wet} process perform positive energy yield for jet biofuel product while $Biodiesel_{wet}$ and $Biodiesel_{RD}$ perform positive energy yield for biodiesel product. Despite of jet biofuel or biodiesel, lipids extracted by dry algae conduct the negative energy output. To compare different routes based on the energy yield despite biofuel quality and quantity, HTL-HRJ process, $biodiesel_{wet}$ and $Biodiesel_{RD}$ process conduct the priorities in energy consumption with similar positive energy gain.

2.4 Uncertainty analysis in life cycle

The quality of upstream CO_2 deliverable defined the quality of downstream algae. The edible algae need cryogenic fractionation purification with benefit for bionutrient while general algae can choose chemical absorption purification with benefit for less energy consumption. The effects of algae cultivation are also complex as high lipid content is associated with lower specific productivity while lower lipid content is associated with higher specific productivity. For assessing the total impacts, the total energy consumptions of different target products with upstream CO_2 deliverable and algae deliverables to downstream biofuel deliverables were calculated quantitatively on edible algae (Fig. 4a) and general algae (Fig. 4b).

Despite lipid derived from edible algae or general algae, HTL-HRJ process performed obviously lower total energy consumptions than HRJ_{wet} process and even HRJ_{dry}. HTL-HRJ process prefers to algae feedstock at 35–45% lipid content with growth rate above 3 $g/m^2.d$ while $Biodiesel_{RD}$ and $Biodiesel_{wet}$ processes also prefer the same upstream algae cultivation as HTL-HRJ process. The high energy consumptions were investigated at algae feedstock with below 15% lipid content in all refining biofuel process. HRJ_{wet} process conducted sensitively to algae feedstock, which perform the low energy consumption only at a small range of around 24% lipid content.

For edible algae, HTL-HRJ process still take advantage in the total energy consumptions despite of mass allocation or energy allocation in comparison with HRJ_{wet} process. For only lipid use despite biodiesel or jet biofuel, all target biofuels conducted negative energy gains, and negative energy gains were also investigated in the wide range of edible algae cultivation despite allocation of by-products (bio-nutrients and glycerin).

For general algae, HTL-HRJ, $Biodiesel_{RD}$ and $Biodiesel_{wet}$ were investigated positive energy gains in the lipid range of 35–45% with glycerin by-product. Mass allocation and energy allocation both achieved the reduction of the total energy consumption, but negative energy gains were also investigated in low lipid content and high lipid content, shown in Fig. 5.

In order to further reduce the potential energy consumptions, the energy consumptions are assessed by the assumption that all thermal heat of the whole life cycle was covered by solar energy or waste heat. Coupling solar energy utilization and by-product effects, the positive energy gains have been investigated at 15–45% lipid content despite of biofuel deliverables derived from general algae or edible algae.

The assessment indicated that allocation is a crucial issue to balance energy, environment and economy decision on target product choice and by-products. Bioactive nutrients as by-product are not only benefit in economy but also in energy consumption. The results further indicated that the integrated algae utilization and waste heat can achieve significantly the reduction of energy consumption.

Modification should couple the upstream source and downstream consequences in the algae biofuel life cycle. The lipid profile of microalgae defined the possible biofuel quantity. For Nannochloropsis, the length of the carbon chain of fatty acids are in the range of C14 - C22 with 16 and/or 18 as the most abundant components [28] [29], which indicated that Nannochloropsis contained the available bioactive nutrient and the appropriate carbon chain for jet biofuel and biodiesel. Jet fuel and diesel are both hydrocarbon molecules but with different carbon number. Jet fuels are mainly in the range of C8 - C16 while diesels are mainly in the range of C12 - C20. Fatty acids of C16 and C18 are appropriate for biodiesel while fatty acids of C16 and C14 are appropriate for jet biofuel. Algae CO_2 fixation will be promising in the direction of cultivating appropriate algae for the target biofuel deliverables and by-product recovery.

3. Conclusions

Coupling transportation distances and purification modes with flue gas concentrations, flue gas with low CO_2 concentration is appropriate for on-site utilization within 10 km while flue gas with above 95% CO_2 is flexible to transportation distance and purification modes.

Specific productivities and CO_2 fixation both comply with negatively logarithmic relationship with lipid contents while lipid contents and profile defined biofuel deliverables. HTL-HRJ, Biodiesel_{RD} and Biodiesel_{wet} were investigated positive energy gains in the lipid range of 35–45% of general algae with glycerin by-product. Negative energy gains were investigated in the wide range of edible algae cultivation despite allocation of by-products (bio-nutrients and glycerin).

Coupling solar energy utilization and by-product effects, the positive energy gains have been investigated at 15–45% lipid content despite of biofuel deliverables derived from general algae or edible algae. Algae CO_2 fixation can be further modified in the direction of cultivating appropriate algae for available target biofuel product and connecting upstream flue gas source.

4. Method

4.1 Goal definition and system boundary

For balancing energy consumption of algal biofuel in quality and quantity with CO_2 sequestration, the boundary of the system involved CO_2 capture and purification and algal final product. The functional units have been defined at energy consumption (MJ) per final mass product (kg) and energy consumption (MJ) per final energy yield (MJ).

The life cycles were classified into three stages, shown in Fig. 1. The first stage is called as CO_2 source and deliverable stage including flue gas capture and purification, and subsequently CO_2 transport as well as CO_2 distribution. Flue gas was captured and purified to remove NOx, SOx and trace metal. By transporting to algae cultivation site, flue gas was distributed into bioreactor. The second stage was defined as algae cultivation and deliverables stage coupling CO_2 absorption and algal biofixation. Nannochloropsis oceanica were cultivated in raceway pond or photobioreactor. The third stage was defined as refining process and fuel deliverable stage, which contains three types of products including algae powder, biodiesel, jet biofuel as well as associated by-products, given in Fig. 6.

There are two pretreatment methods to obtain biofuel precursor, lipid derived from solvent extraction and biocrude derived from hydrothermal liquification. Algal lipids or biocrude as the precursors are hydrotreated by two-stage upgrading into jet biofuel. For jet biofuel, there are three types of jet biofuel including hydrotreating lipid extracted from algae slurry into jet biofuel (HRJ_{wet}), hydrotreating lipid extracted from algae powder into jet biofuel (HRJ_{dry}), and hydrotreating hydrothermal biocrude into jet biofuel (HTL-HRJ). There are two pretreatment methods to obtain biodiesel precursors, methyl fatty acid ester derived from solvent extraction with methanol and biocrude derived from hydrothermal liquification. Methyl fatty acid esters are further purified into $Biodiesel_{dry}$ and $Biodiesel_{wet}$ while biocrude is hydrotreated by one-stage upgrading into renewable diesel ($Biodiesel_{RD}$).

4.2 Computational framework and approach

Computational framework is integrated 3 sub-models, including CO_2 source and deliverable model, algae cultivation and deliverable model, refining process and fuel deliverable model. CO_2 deliverable model includes CO_2 capture and purification, CO_2 transport, and CO_2 distribution. For CO_2 capture and purification, there are four methods involved in CO_2 deliverable model including chemical absorption, physical adsorption, membrane separation, and cryogenic distillation. For CO_2 transport, feasible transportation modes for choice include by tankers and pipelines based on the distance and CO_2 concentration. For CO_2 distribution, raceway pond and photobioreactor are involved with consideration of scale effects.

Algae cultivation and deliverable model includes algae growth with CO_2 absorption and deliverables of algae powder and algae slurry. Biofixation reactors including raceway pond and photobioreactor are involved for CO_2 absorption to cultivate Nannochloropsis. The energy consumption involved in the model are classified direct energy consumption (the power for algae suspension, power for pumping nutrient and water provision), and indirect energy consumption (nutrient supplement). Nutrients are supplied according to the stoichiometric consumption in accordance with Nannochloropsis substance contents (carbohydrate, protein, lipid, and ash) and element contents (carbon: nitrogen: phosphorus) with compensation 5% N-nutrient loss in volatilization.

Refining process and fuel deliverable model[15] is established as an integrated computerized model for assessing refining process and biofuel deliverable. The solvent extraction pretreatment process was considered homogenization and solvent extraction as well as solvent recovery derived from algae powder or algae slurry. Hydrothermal liquification pretreatment was considered stream consumption and exchanger efficiency. Lipid or biocrude as the precursors were upgraded into jet biofuel or biodiesel. Hydrogen consumption, thermal heat and electricity consumption were involved in hydrotreating process. The purification of methyl fatty acid ester into biodiesel was considered in $Biodiesel_{dry}$ and $Biodiesel_{wet}$. The input and output of material and energy are involved in the computation framework. The materials of catalyst, hydrogen, and methanol are also involved as the indirect energy consumptions into computation framework.

Allocation methods were established based on dimensionless for assessment. Mass allocation method complies with mass ratio ($Mass_{biofuel}/Mass_{algae}$) while energy allocation method complies with energy ratio ($Energy_{biofuel}/Energy_{algae}$) and energy input efficiency

$$\left(Energy_{biofuel} \Big/ (Energy_{algae} + input\ energy)\right).$$

As the result, energy load and mass load not only have practical physical significance but also have additivity and comparability. Energy consumptions of input materials are defined as H_2 165.5 MJ/kg,Methanol 11.98 MJ/kg,$(NH_4)_2HPO_4$ 17.081 MJ/kg and Urea 28.949 MJ/kg.

4.3 Life cycle inventory data

The inventory data in CO_2 source and deliverable model include purification, transportation, and distribution. Flue gases derived from coal power station consist of 10–20% CO_2 at 1.3 kg/m^3 and N_2 (77%), H_2O (9–14%), O_2 (2–6.5%), NO (60–1500 mg/Nm^3), NO_2 (2–75 mg/Nm^3), SO_2 (0–800 mg/Nm^3), SO_3 (0–32 mg /Nm^3), CxHy (0.008–0.4 mg/Nm^3), CO (2.5–5 mg/Nm^3), particulate matter (120–800 mg/Nm3), halogen acids, and heavy metals[30, 31].

For the energy consumption in capturing and purifying, chemical absorption[32–34] of flue gas can be achieved at 1.19–1.22 MJ/kgCO_2 with 95–98% CO_2 recovery efficiency while pressure swing adsorption[33, 34] of flue gas was at 0.58–0.64 MJ/kgCO_2 with 85–90% recovery efficiency. Membrane Separation[33–35], excludes the other parts of the flue gas by only CO_2 through the membrane wall. Commercially available uses can be obtained with energy demands of 0.25–0.27 MJ/kgCO_2 with 82–88% of CO_2 recovery efficiency by polymeric gas separation membranes. Cryogenic separation[34, 36] with 90–95% of CO_2 recovery efficiency by condensing at an extremely low temperature, excludes the other parts of the flue gas by liquified CO_2 as liquid phase. The energy consumption in low-pressure pipeline transport are collected from literature[34] [36] while the energy consumption in CO_2 distribution are calculated coupling the pump efficiency and depth of bioreactor [37].

The LCI data of Nannochloropsis growth, were collected coupling lipid content with specific productivity by literature[38–44] and actual Nannochloropsis oceanica powder production plant in China[1]. The influence coefficient of the external irradiation intensity, irradiation time, temperature was quantified coupling CO_2 distribution and nutrient supply.

Table 1

life cycle inventory in product stage

Biofuel precursor (lipid) (ZHANG, C, et al., 2018)		**Biofuel precursor (biocrude) (HAGHIGHAT, P, et al., 2019; SHENG, L, et al., 2018; TANG, X, et al., 2016; ZHANG, C, et al., 2016; ZHANG, C, TANG, X and YANG, X, 2018)**	
Extraction lipid efficiency: homogenization 90–94%; lipid extraction 95% (dry); 93% (wet); Material inputs: hexane 45.4 g/kg_{lipid}; methanol0.15 kg/kg_{lipid}; Energy use: homogenization 0.246 kWh elec./kg_{algae}; lipid extraction 0.51 kWh elec. + 6.83 MJ heat /kg_{lipid} Product: lipid 0.118 kg – 0.44 kg/kg_{algae} By-product: residue (fertilizer) 0.55–0.88 kg/kg_{algae}, glycerin 0.145 kg/kg_{lipid}		Energy use: Hydrothermal liquefication 0.096 kWh + 2.24 MJ heat/$kg_{biocrude}$. Product: Biocrude 0.177–0.66 kg/kg_{algae} By-product: glycerin 0.145 g/g_{lipid}, nutrient with vitamin E and sterol 5% kg/kg_{lipid}	
Lipid to jet biofuel(SHI, Z, et al., 2018)	Lipid to biodiesel(CLARENS, A F, HAGAI, N, RESURRECCION, E P, WHITE, M A and COLOSI, L M, 2011; LIAW, B, JASON, Q, BRYAN, W and THOMAS, B, 2010; MU, D, et al., 2017)	Biocrude to jet biofuel(LIU, Z and YANG, X, 2018; ZHAO, B, et al., 2017; ZHAO, B, et al., 2016)	Biocrude to biodiesel(FRANK, E D, et al., 2013; ROBERTS, G W, et al., 2013; SANDER, K, et al., 2010)
Efficiency: 65 -74.2% Material inputs: Hydrogen 0.050 kg/kg_{HRJdry}; Hydrogen 0.0504 kg/kg_{HRJwet}; Catalyst Ni/Mo/ Al_2O_3 Energy use: Hydrotreating 1.7 kWh elec. /kg_{HRJ}; Product: Jet biofuel 0.062–0.248 kg/kg_{algae} By-product: Gas (Methane, Ethane, Propane, CO) Naphtha 0.015–0.058 kg/kg_{algae}	Efficiency: transesterification 99 wt.% lipid; Material inputs: HCl = 0.085 $kg/kg_{biodiesel}$; Energy use: transesterification = 0.09 kWh elec. + 1.7 MJ heat/kg_{diesel}. Product: Biodiesel 0.118 g – 0.44 g/g_{algae}	Efficiency: 64.5–73.2% Material inputs: Hydrogen 0.0719 $kg/kg_{HTL-HRJ}$ Cat. Ni/ Al_2O_3, Ni/Mo/ Al_2O_3, Energy use: Hydrotreating (two-stage upgrading) 2.2 kWh elec. /kg jet fuel. Product: Jet biofuel 0.103–0.386 kg/kg_{algae} By-product: Naphtha 0.011–0.043 kg/kg_{algae} Gas (Methane, ethane, Propane, CO)	Material inputs: Hydrogen 0.063 $kg/kg_{biodiesel}$ Cat. Ni/Mo/ Al_2O_3, Energy use: Hydrotreating (one-stage upgrading) = 1.5 kWh elec./$kg_{biodiesel}$. Product: Biodiesel 0.14–0.48 kg/kg_{algae} By-product: Naphtha 0.023–0.086 kg/kg_{algae} Gas (Methane, Ethane, Propane, CO)

The LCI in refining process and biofuel deliverables, were collected based on Greet, literature, and our previous research, given in Table 1. In lipid extraction pathway, lipid extraction was extracted by hexane extraction. The energy consumption and efficiency in homogenization stage are 0.246 kWh elec./kg dry algae per dry metric ton with 90%. The lipid in hexane extraction stage conform to the lipid content in algae with extraction efficiency 95% for dry extraction and 93% for wet extraction. Algae lipid$_{dry}$ ($C_{18.18}H_{33.25}O_{3.98}N_{0.22}$) derived from dry algae and Algae lipid$_{wet}$ ($C_{18.18}H_{32.61}O_{3.76}N_{0.20}$) was hydrotreated to aviation fuel (HRJ$_{dry}$ $C_{14.81}H_{28.92}$, HRJ$_{wet}$ $C_{13.84}H_{27.3}$) based on our previous research[45] while algae lipid was transformed by transesterification into methyl fatty acid ester, namely biodiesel. In HTL biocrude pathway, algae biocrude was obtained by hydro-liquification. The energy consumption includes the heat and pump for feedstock. Algae biocrude ($C_{15.30}H_{26.46}O_{3.44}N_{0.73}$) was hydrotreated to aviation fuel (HTL-HRJ $C_{12.64}H_{25.99}$) with 64.5% biofuel yield with 95% jet fuel based on our previous research[46, 47] and to renewable biodiesel with 73% biofuel with biodiesel 95%.

Declarations

Ethics approval and consent to participate

Not Applicable

Consent for publication

Not Applicable

Competing interests

The author declare that they have no competing interests.

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Authors' contributions

All author read and approved the final manuscript.

Availability of Data and Material

All data and material have been involved in method.

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Figures

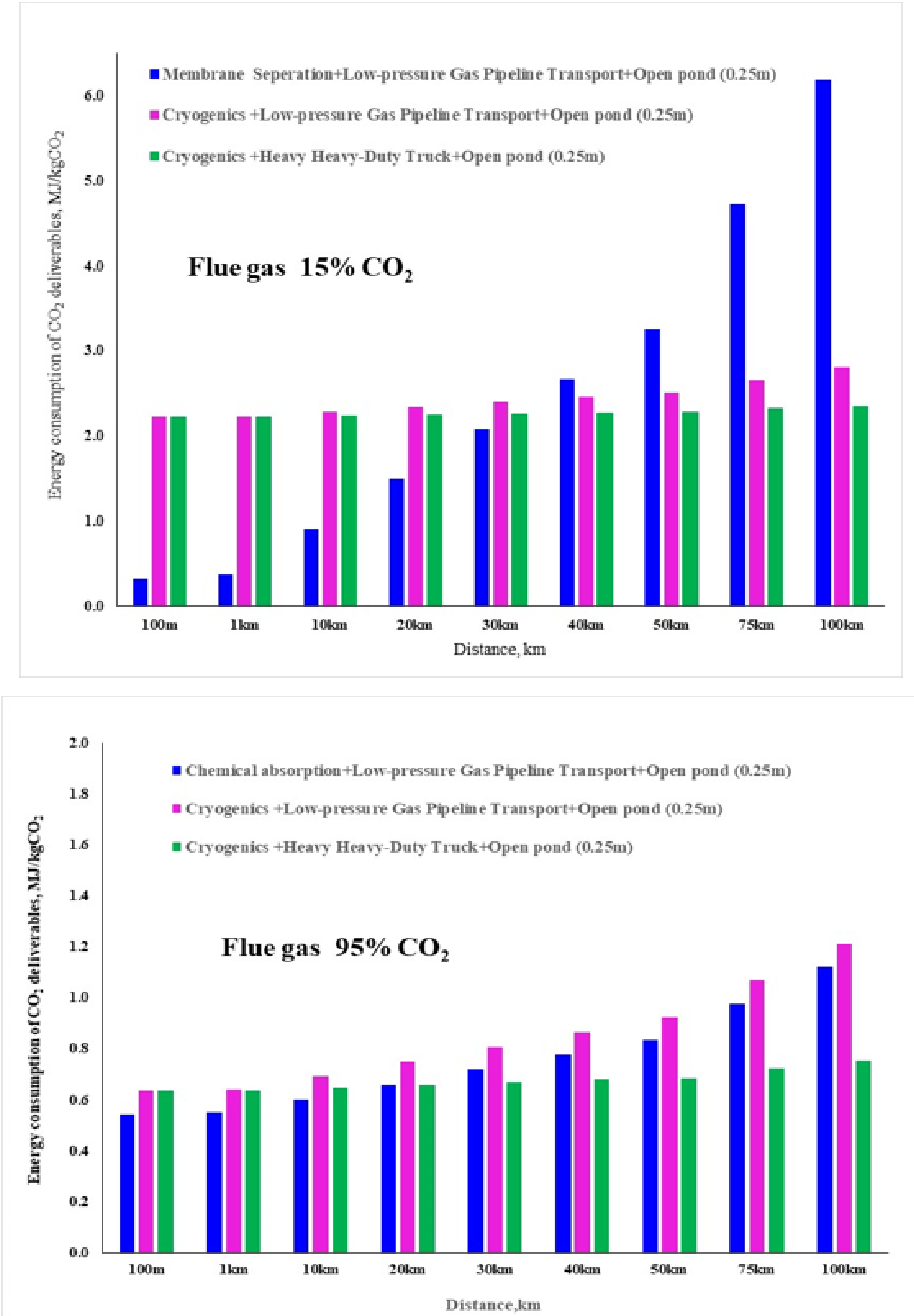


Figure 1

Energy consumption in CO2 deliverables coupling purification, transportation and distribution a. 15% flue gas; b. 95% flue gas

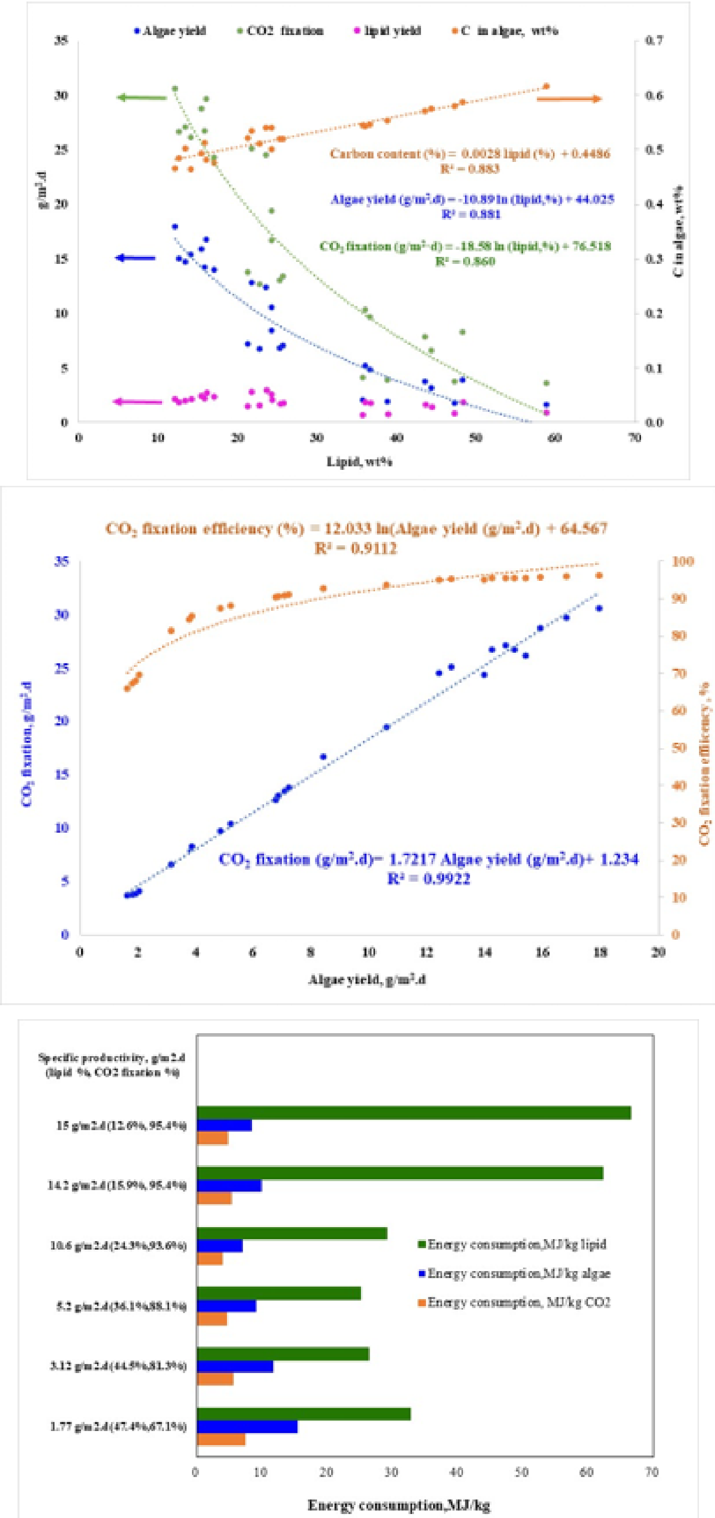


Figure 2

Quantitative relationship related with algae deliverables a. Quantitative relationship of lipid content with algae specific productivity and CO2 fixation; b. Quantitative relationship of algae specific productivity with CO2 fixation; c. Energy consumption related with lipid content, algae productivity and CO2 fixation

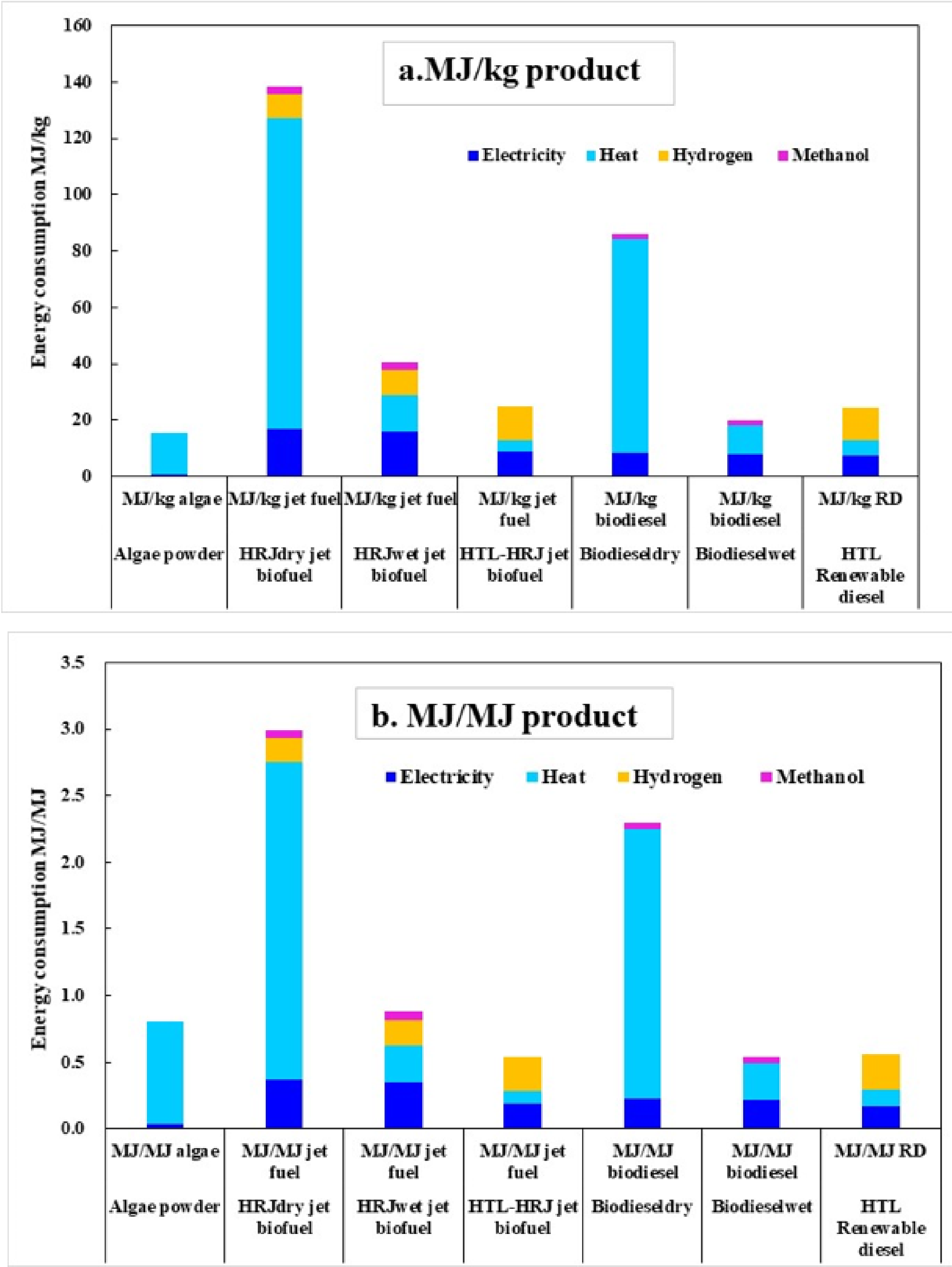


Figure 3

Effects of refining process on energy consumption a. MJ/kg product; b. MJ/MJ product

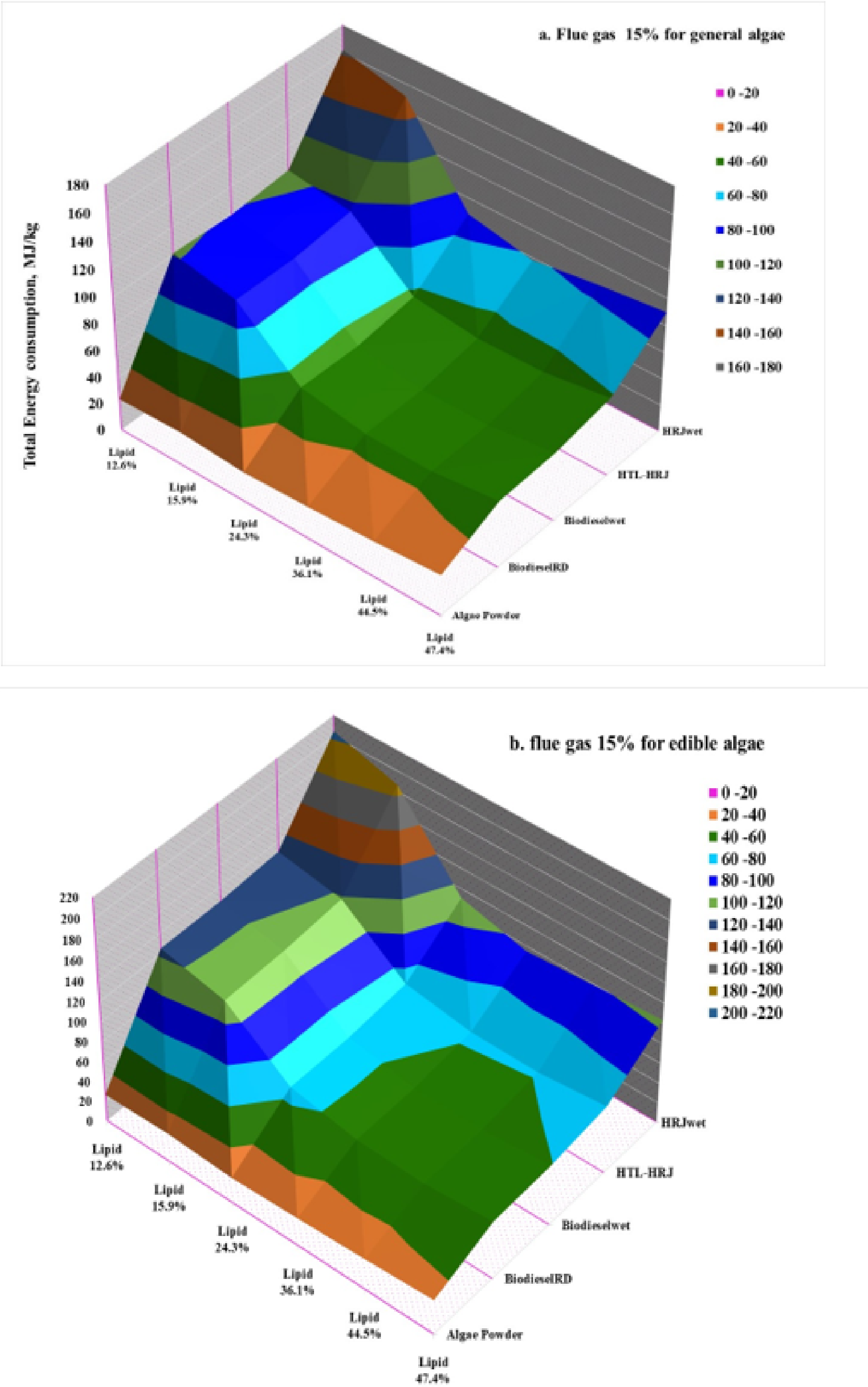
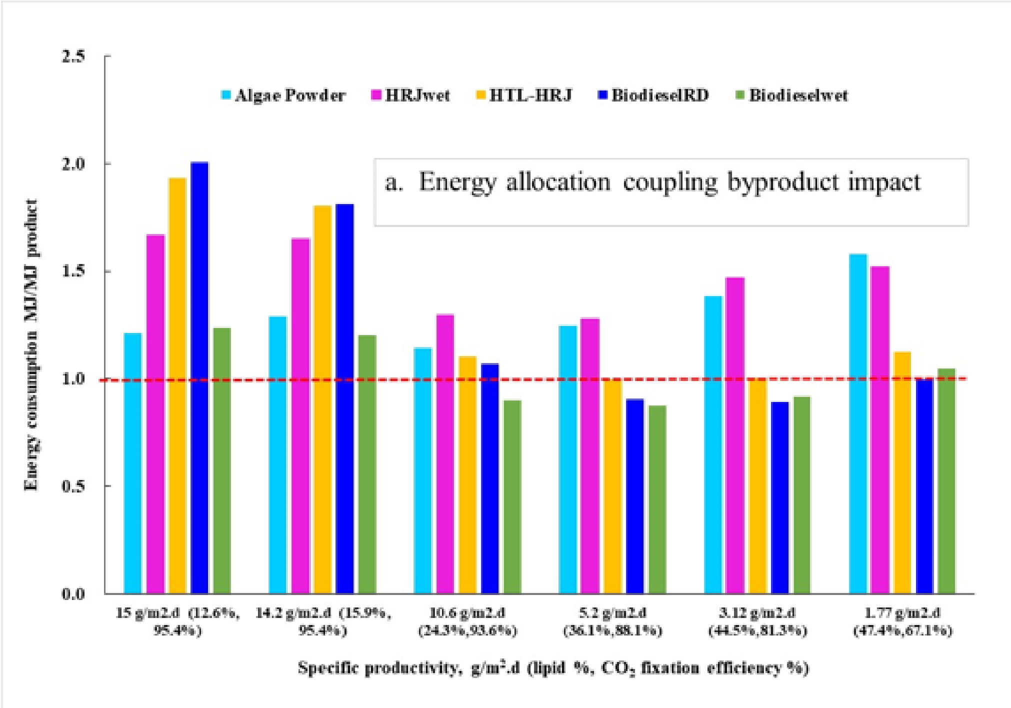


Figure 4

Total energy consumption with two types of algae for biofuel a. flue gas 15% for general algae; b. flue gas 15% for edible algae;



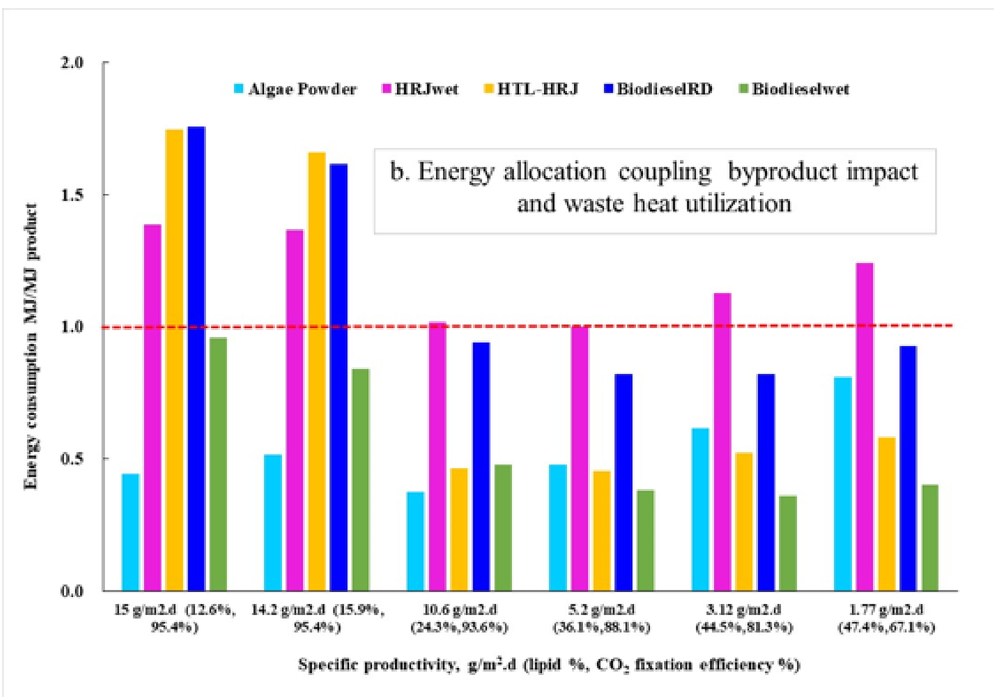


Figure 5

Total energy consumption in life cycle based on energy allocation - general algae for biofuel a. byproduct impact; b. byproduct impact and waste heat utilization

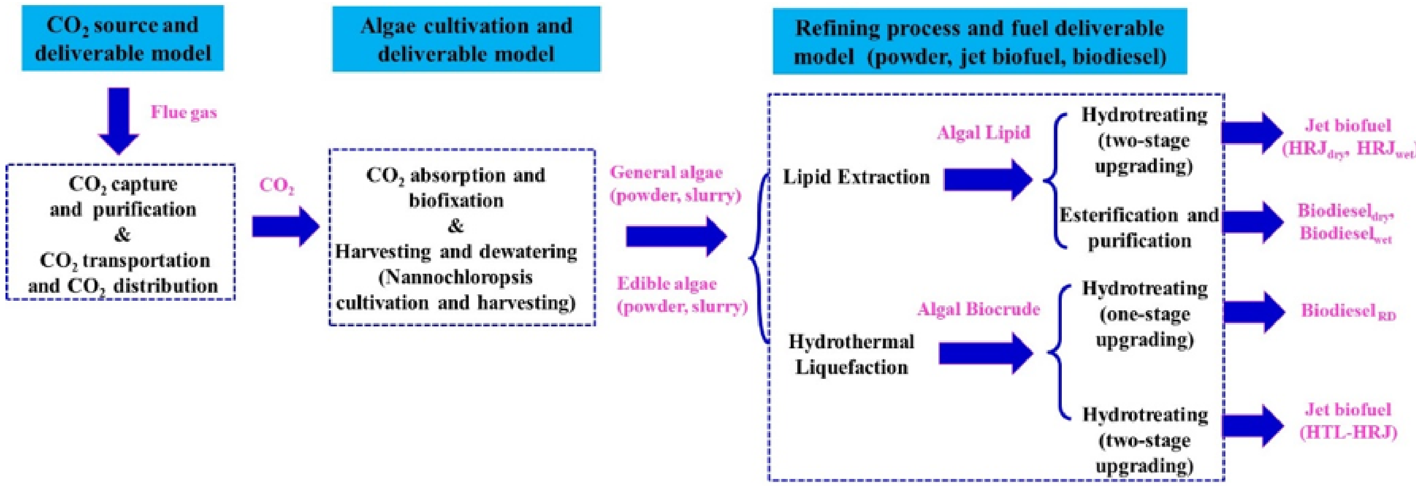


Figure 6

System boundary definition

Supplementary Files

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