



# Exploring the feasibility of producing sustainable aviation fuel in the UK using hydrothermal liquefaction technology: A comprehensive techno-economic and environmental assessment



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## ABSTRACT

Carbon emissions from the aviation industry are a significant concern and the adoption of sustainable aviation fuel has the potential of mitigating the environmental impacts. Hydrothermal liquefaction (HTL) has great potential to produce sustainable aviation fuel employing organic waste feedstock but requires further development to reduce costs and the environmental impact. This study focuses on examining the feasibility of an integrated HTL plant in the UK whilst investigating the potential to improve the energy efficiency of the process through heat integration and resource recovery from waste streams. The methodology adopted includes modelling an integrated HTL plant with a feed throughput of 10 t h<sup>-1</sup> using Aspen Plus simulation approach. Techno-economic, regional resource and carbon footprint assessment are conducted on three different HTL configurations, i.e. a base case without energy and resource recovery; an HTL with heat integration; and an HTL with energy and resource recovery. Three different feedstocks (algae, food waste and sewage sludge) are investigated with sewage sludge feedstock found to have the lowest minimum fuel selling price of 0.50 £ l<sup>-1</sup>. Heat integration results in a 96.4% and 77.8% decrease in heating and cooling utilities and the economic assessment indicates that heat integration and resource recovery can reduce the minimum fuel selling price by 10.5% compared to the base case. The regional resource assessment reveals that 22.8% of UK jet fuel demand can be met with the technology. The carbon footprint assessment demonstrates that with maximum production, the technology can result in a 18.3% reduction of CO<sub>2</sub> emissions relative to current aviation emissions. This study signifies that the integrated HTL process could play a pivotal role in mitigating carbon emissions in the aviation industry.

## 1. Introduction

Aviation provides a rapid global transportation network and is pivotal for many industries from trade to tourism. The industry currently transports approximately 3.8 billion passengers annually and 35% of world trade calculated by the value of goods shipped (ATAG, 2017). Aviation generated 895 million tonnes of CO<sub>2</sub> in 2018 and is responsible for 2% of globally human-induced carbon dioxide emissions (ATAG, 2017). In the UK, greenhouse gas (GHG) emissions from the aviation sector amounted to 39.3 Mt of CO<sub>2</sub> in 2017, contributing to 5.1% of total UK emissions (CCC, 2020). Decarbonising the aviation sector through deployment of sustainable aviation fuel (SAF) is exigent to achieve the net zero target in the UK by 2050. SAF has the potential to become “drop-in” fuel which can be incorporated into existing airport fuelling systems, similar to the conventional jet fuel (ATAG, 2017). There are

currently a number of ASTM certified technologies that can be adopted to produce SAF, including Fischer-Tropsch, Hydroprocessed esters and fatty acids and alcohol-to-jet (IRENA, 2017). There are approximately four emerging production pathways awaiting ASTM certification including pyrolysis, hydrothermal liquefaction (HTL), aqueous phase reforming, and aerobic fermentation of sugars (IRENA, 2017). HTL is chosen as the focus of this study, as an emerging production pathway that has shown promising potential to produce SAF using wet biomass such as municipal solid waste and sewage sludge, so reducing the need for dewatering (Katakajwala et al., 2020). The major advantage of HTL is its versatility to process a wide range of feedstock whilst producing a bio-oil intermediate with low oxygen and high energy content (37 MJ kg<sup>-1</sup>) (Snowden-Swan et al., 2017).

The HTL reactor centres on the processing of biomass slurries with approximately 20% solids content under moderate temperature (250–550 °C) and high pressure (50–250 bar) (Snowden-Swan et al.,

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### Abbreviation List

AC	Annualised capital costs
AP	Aqueous phase
BC	Base cost
CEPCI	Chemical Engineering Plant Cost Index
CHG	Catalytic hydrothermal gasification
CRF	Capital recovery factor
GHG	Greenhouse gas
GIS	Geographic Information System
HTL	Hydrothermal liquefaction
MFSP	Minimum fuel selling price
SAF	Sustainable aviation fuel
TCC	Total capital costs
WWTP	Wastewater treatment plant

2017). This poses a number of challenges for commercial scale up, such as the high energy requirement and the pumpability of slurries with high solid contents (Biller and Roth, 2018). Another challenge is the upgrading of the biocrude oil, specifically in reducing the nitrogen content to make it more compatible with fuel specifications (Castello et al., 2019). The economic and environmental implications of an external input of hydrogen (Qiang and Wang, 2020) for use in upgrading also needs to be investigated. HTL is currently limited to lab-scale and requires additional process optimisation and further development before reaching commercialisation with a technology readiness level of 4–5 (IATA, 2015).

Commercial HTL plants require significant investment and investors need to have confidence that supply demands of feedstock can be continuously met and thus, assessment of their availability is essential. Skaggs et al. (2018) conducted a study of available organic waste feedstock potentially available for the HTL technology in the US finding that the technology can potentially meet 23.9% of current US demand of aviation kerosene. As well as the availability of feedstock, there is a strong motivation to explore a more robust method to both reduce the carbon footprint of the process and increase the economic viability such as through resource recovery strategies as seen in research by Ng et al. (2019) in sustainable waste management, Ong et al. (2018) in an integrated HTL plant and Yang et al. (2020) in treatment of HTL wastewater, which is currently underexplored. Research by Palomino et al. (2020) revealed that storing biocrude produced from HTL before upgrading is feasible as the intermediate is somewhat stable in contrast to the product from pyrolysis. It must be investigated whether the benefits of economies of scale with many localised HTL plants and a centralised upgrading plant, similar to the conceptual design by Snowden-Swan et al. (2017), outweigh the benefits of heat integration and resource recovery in an integrated plant which includes both HTL and upgrading in a single facility. Whilst techno-economic (Reißmann et al., 2018) and environmental assessments (Frank et al., 2013) have been conducted on separate upgrading and HTL plant facilities further research is required to investigate the economic viability and environmental impact of integrated plant designs, similar to research performed by Zhu et al. (2014). The majority of current research surrounding the HTL process involve the use of algae feedstock such as the studies by Frank et al. (2013), in the life-cycle emissions from HTL using algae, and Tang et al. (2020), in optimising the process of HTL using algae, and further research is needed to evaluate the feasibility of using different feedstock such as food waste and sewage sludge.

The novelty of this research lies in the inclusion of energy integration and resource recovery strategies within HTL system design to enhance product yield, energy efficiency and economic performance while

minimising the environmental impacts on aviation fuel production and consumption. The objectives include (i) investigating the effect of using different feedstock (i.e. algae, food waste and sewage sludge) on biocrude yield; (ii) improving energy efficiency of the system using pinch analysis; (iii) enhancing resource efficiency by valorising the by-product/residue stream; (iv) assessing the carbon footprint of the integrated plant and (v) exploring the level of jet fuel demand that can be met in the UK by utilising local organic waste and algal resources.

This paper is structured as follows: The conceptual design methodology for HTL process development and the process modelling of different HTL configuration is presented in Section 2. Section 3 presents the results of the economic analysis, regional resource assessment and environmental impact assessment of the different case studies modelled in Section 2. The conclusions of the study are presented in Section 4.

## 2. Methods

### 2.1. Conceptual design framework for HTL system

A conceptual design framework for modelling and integrated techno-economic-environmental assessment of HTL plant is presented in Fig. 1. This study employs process design and modelling methods to construct a conceptual plant for three different case scenarios. This includes the base case HTL plant without heat integration; Case 1 where HTL incorporates heat integration; and Case 2 which incorporates resource recovery from by-product/residue streams and heat integration. In these case studies, algae, food waste and sewage sludge have been considered as different feedstock. The modelling of these different cases provides information for analysis which includes a techno-economic and carbon footprint assessment that examines the environmental impact of the HTL plant. A regional resource assessment is conducted to estimate the level of UK jet fuel demand that can feasibly be met by utilising available organic waste resources and algae. The analysis provides important guidance for investors and policy makers on the choice of feedstock and system specification which is crucial for establishing integrated HTL technology in the UK.

**Scope definition:** HTL upgrading has been included within the system boundary to explore the potential for heat integration and resource recovery in an integrated plant as well as to avoid transportation costs of the intermediate biocrude to a centralised upgrading plant. Wastewater treatment plant (WWTP) has also been included within the system boundary to reduce nitrogen and ammonia content in the waste aqueous stream, in compliance with environmental standards at headworks.

### 2.2. Process design and modelling

The modelling and design is based on the previous conceptual design for a sewage sludge HTL plant by Snowden-Swan et al. (2017). The HTL plant model was constructed in Aspen Plus, a widely used process simulation package in the refinery and petrochemical industries. An evolutionary design approach (Hernandez and Ng, 2018) was adopted, starting from reaction, followed by separation, heat exchangers and utilities. The Soave-Redlich-Kwong property method was selected as it was the most capable of both predicting the immiscibility of biocrude oil with water and matching results from the literature on phase separation (Ramirez, 2018). Kinetics of the HTL reactor is based on research by Valdez et al. (2014) and the modelled reactions are obtained from Toor et al. (2011) who used biomass feedstock and Raza (2014) who used algae feedstock. The availability of data on the kinetics and modelled reactions for the HTL reactor and upgrading reactions were limited and data were obtained from where it is available from a range of research papers. Likewise, experimental data which was used to validate the model was also obtained from a range of studies including work by Palomino et al. (2020), Iacovidou et al. (2012) and Vo et al. (2016). Due to the lack of available data on commercial-scale pilot studies of continuous plants, it was assumed that the kinetics and yields will not

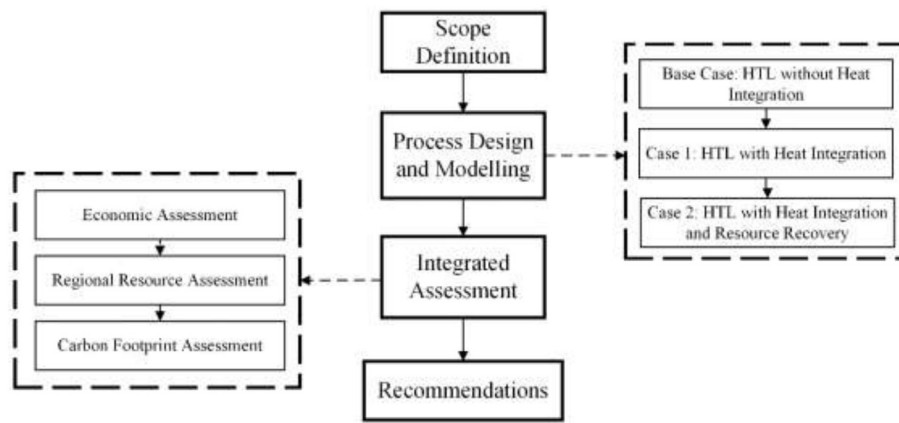


Fig. 1. Conceptual design framework for modelling and integrated techno-economic-environmental assessment of HTL technology.

differ widely from the lab-scale experiments for the modelling conducted in this study.

The following HTL configurations have been modelled:

- Base case:** The base case of the designed plant is devoid of any heat integration and recovery of by-product/residue streams.
- Case 1:** Heat integration analysis was performed on the HTL system in view of achieving maximum energy recovery. Pinch analysis using the problem table, composite curve and grand composite curve methods was employed (Towler and Sinnott, 2019).
- Case 2:** Resource recovery from by-product/residue streams from HTL as well as heat integration have been incorporated in the HTL system design. Catalytic hydrothermal gasification (CHG) is used to recover organic resources from the aqueous phase (AP) which is chosen due its ability to produce hydrogen for use in upgrading.

### 2.3. Integrated assessment

#### (i) Economic assessment

The economic assessment involved estimating the total capital and operating costs and profitability analysis of the plant. A flow chart showing the economic assessment and the associated cost components is presented in Fig. 2. Estimation methods were adopted from the techno-economic assessment conducted in a Snowden-Swan et al. report (2017) to calculate the costs of the various components such as the equipment costs. The land costs were scaled from the report by Knorr et al. (2013).

Equation (1) was used for calculating the installation costs of

equipment where the costs were scaled from the base costs (BC) and exponents from Knorr et al. (2013) and Snowden-Swan et al. (2017) reports. The installation costs of equipment were updated to the present year using Equation (1) by applying the Chemical Engineering Plant Cost Index (CEPCI) (Sadhukhan et al., 2014).

$$\text{Installation Cost} = BCX \left( \frac{\text{Actual Equipment Flowrate}}{\text{Original Equipment Flowrate}} \right)^{\text{Scale Factor}} \times \left( \frac{CEPCI_{\text{baseyear}}}{CEPCI_{\text{literatureyear}}} \right) \quad (1)$$

The operating costs are the sum of fixed and variable operating costs (Sadhukhan et al., 2014). Fixed operating costs include costs of personnel, overhead and maintenance costs and taxes. The value for the personnel costs was based on estimations from Snowden-Swan et al. (2017). Variable operating costs depend on electricity and utility requirements which were estimated using Aspen Plus. The steam input was assumed to be purchased from external suppliers whilst the required steam mass flow rates were calculated using standard mass enthalpy equations (Sadhukhan et al., 2014). Similarly, hydrogen was also assumed to be purchased from external suppliers. The variable operating costs also include the cost of feedstock, quicklime for the aqueous phase treatment, wastewater discharge fee for sending to headworks, water make-up and hydrogen for upgrading.

Discounted cash flow analysis (Sadhukhan et al., 2014) was applied to estimate the minimum fuel selling price (MFSP) of the biocrude. The MFSP is defined as the selling price of the fuel that results in a net present value of the project equal to zero and is calculated using equation (2). A 10% discounted cash flow rate of return was assumed for a 30-year plant life. The capital recovery factor (CRF) defined in equation (3) was used to

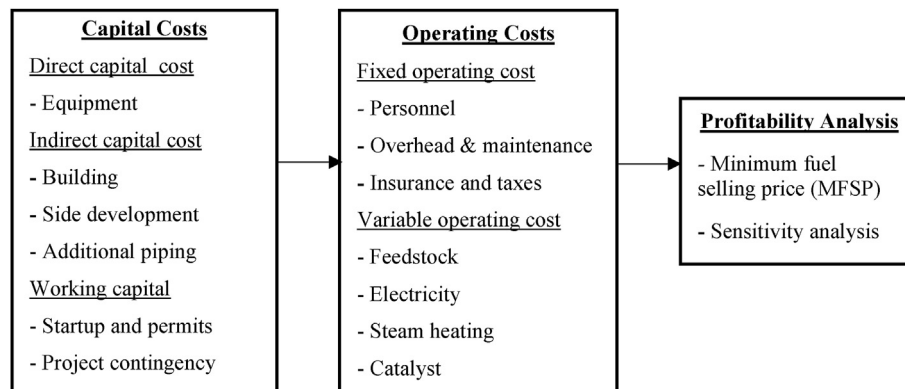


Fig. 2. Methodology adopted for the economic assessment including a breakdown of the capital and operating cost and the main components of the profitability analysis.

compute the investment in capital costs during subsequent years after construction where  $r$  refers to the discount rate and  $T$  refers to the plant life (Ng and Martinez-Hernandez, 2020). The annual costs were calculated by multiplying the total capital costs (TCC) with the CRF as show in Equation (4) (Ng and Martinez-Hernandez, 2020).

$$\text{MFSP} = \frac{\text{Annual Cost}(\text{£ y}^{-1})}{\text{Aviation Fuel Production Rate}(\text{1 y}^{-1})} \quad (2)$$

$$\text{CRF} = \frac{r(1+r)^T}{(1+r)^T - 1} \quad (3)$$

$$\text{Annual Cost} = \text{TCC} \times \text{CRF} \quad (4)$$

#### (ii) Regional resource assessment

A regional resource assessment was conducted to examine the level of jet fuel demand that can be met by utilising local organic waste feedstock and algae. This was calculated by combining the yield of biocrude obtained from the kinetic modelling with the availability of organic resources found in the literature for algae (POST 2011), food waste (HofC, 2017) and sewage sludge (Trust in Water, 2020). Geographic Information System (GIS) mapping using Paintmaps software was performed to assess the biocrude production potential for different regions in the UK. The UK is divided into its many constituent counties and the distribution of food waste in landfills and sewage sludge in WWTP's were sourced from the urban waste water treatment directive (UWWTD, 2020) and from the Defra and the Food and Drink Federation (DEFRA, 2008).

#### (iii) Carbon footprint assessment

The carbon footprint assessment was carried out based on the Greenhouse Gas Protocol (2015) to evaluate the amount of GHG emissions for producing 1 tonne of aviation fuel from the HTL technology. The present study considers cradle-to-grave analysis and the boundary begins from the collection of the feedstock and continues until the combustion of the fuel in jet engine. The GHG emissions resulting from the transportation of feedstock, the production process of the aviation fuel and the combustion of the fuel in the jet engines were assessed and quantified using GHG emission factors. The production GHG emissions included emissions from transportation of feedstock and fuel, electricity use and the energy use by the HTL, upgrading and CHG reactors which were estimated using the Aspen Plus model of the plant. Equation (5) was applied to calculate the GHG emissions per kilogram of aviation fuel produced.

$$E_{\text{GHG}} = \sum_{j=1}^J \frac{m_{p,j}e_{p,j} + m_{g,j}e_{g,j}}{m_f} + e_{c,j} \quad (5)$$

where.

$E_{\text{GHG}}$ : GHG emissions per kilogram of aviation fuel (kg CO<sub>2e</sub>/kg aviation fuel);

$m_p$ : Mass or energy flowrate through the specific production processes (kg h<sup>-1</sup> or kW);

$m_g$ : Mass flowrate of feedstock input (kg h<sup>-1</sup>);

$m_f$ : Mass flowrate of aviation fuel produced by the HTL plant (kg h<sup>-1</sup>).

$e_{g,j}$ : Specific emission factor for the absorbed emissions during the growth of algae or avoided emissions from food waste in landfills or WWTP processing of sludge (kg CO<sub>2e</sub>/(kg of feedstock));

$e_{p,j}$ : Specific emission factor during the production process (kg CO<sub>2e</sub>/(kg or kW));

$e_{c,j}$ : Specific emission factor during combustion in jet engines and flight (kg CO<sub>2e</sub>/(kg of aviation fuel));

## 2.4. Feedstock

Modelling of the HTL plant begins by compositional analysis of the biomass feed which was divided into proteins, carbohydrates and lipids. It was assumed that there was an equal distribution of the constituent components that make up the proteins, carbohydrates and lipids (Raza, 2014). The resulting mass fractions (dry basis) for the individual components in the three different feedstocks, i.e. algae, food waste and sewage sludge are presented in Table 1. These feedstocks are composed of different moisture content with algae having 86% of moisture, whilst food waste and sewage sludge have 85% and 75% of moisture.

## 2.5. Reaction modelling and validation

### 2.5.1. HTL reaction

The kinetic model proposed by Valdez et al. (2014) was adopted in the present study. Independent reaction pathways were formulated between the components of the feedstock (proteins, carbohydrates and lipids) as first order reactions to produce the AP products and biocrude oil. There are reversible interconversions between the AP products and the biocrude and further conversion to gaseous products (Vo et al., 2017).

Equations 6–11 show the first order rate equations for HTL reactions (Valdez et al., 2014). The variables  $x_{1,p}$ ,  $x_{1,c}$ ,  $x_{1,l}$ ,  $x_2$ ,  $x_3$ , and  $x_4$  correspond to the relevant mass fractions of proteins, carbohydrates, lipids, AP products, biocrude oil and gaseous products. These first order differential equations were solved simultaneously using the *ode45* function in MATLAB (version 2016b) to yield the different product fractions. The kinetic parameters are a function of temperature and have been modelled using the Arrhenius equation. The parameters derived and evaluated from multiple sources in the literature have been validated using experiment data from Vo et al. (2017) and Valdez et al. (2014).

$$\text{Proteins} : \frac{dx_{1,p}}{dt} = -(k_{1,p} + k_{2,p})x_{1,p} \quad (6)$$

$$\text{Carbohydrates} : \frac{dx_{1,c}}{dt} = -(k_{1,c} + k_{2,c})x_{1,c} \quad (7)$$

$$\text{Lipids} : \frac{dx_{1,l}}{dt} = -(k_{1,l} + k_{2,l})x_{1,l} \quad (8)$$

**Table 1**

Composition of algae, food waste and sewage sludge (dry basis).

	Algae (KRS101) (Mass Fraction)	Food waste (Mass Fraction)	Sewage Sludge (Mass Fraction)
<b>Protein</b>	0.30	0.55	0.416
Valine (C <sub>5</sub> H <sub>11</sub> NO <sub>2</sub> )	0.075	0.138	0.104
Leucine (C <sub>6</sub> H <sub>13</sub> NO <sub>2</sub> )	0.075	0.138	0.104
Alanine (C <sub>3</sub> H <sub>7</sub> NO <sub>2</sub> )	0.075	0.138	0.104
Serine (C <sub>3</sub> H <sub>7</sub> NO <sub>3</sub> )	0.075	0.138	0.104
<b>Carbohydrate</b>	0.058	0.17	0.411
Glucose (C <sub>6</sub> H <sub>12</sub> O <sub>6</sub> )	0.058	0.17	0.411
<b>Lipid</b>	0.575	0.13	0
Triolein (C <sub>57</sub> H <sub>104</sub> O <sub>6</sub> )	0.575	0.13	0
<b>Ash</b>	0.067	0.15	0.173
<b>References</b>	Vo et al. (2016)	Iacovidou et al. (2012)	Skaggs et al. (2018)

$$\text{Aqueous phase Products: } \frac{dx_2}{dt} = -(k_4 + k_5)x_2 + k_{1,p}x_{1,p} + k_{1,l}x_{1,l} + k_{1,c}x_{1,c} + k_3x_3 \quad (9)$$

$$\text{Biocrude: } \frac{dx_3}{dt} = -(k_3 + k_6)x_3 + k_{2,p}x_{1,p} + k_{2,l}x_{1,l} + k_{2,c}x_{1,c} + k_4x_2 \quad (10)$$

$$\text{Gaseous products: } \frac{dx_4}{dt} = k_5x_2 + k_6x_3 \quad (11)$$

The *fmincon* function in MATLAB was used to identify the values of the kinetic parameters that minimise the least-squares error between the experimental and model yields in the literature for the biocrude, AP, gas, and solid fractions (Valdez et al., 2013). The solids portion of the product from the reactor was modelled as the total sum of ash content in the original input and the unreacted proteins, lipids, and carbohydrates ( $x_1 - x_{1,p} + x_{1,l} + x_{1,c}$ ). The model reveals that the lipids and proteins fraction were the most responsible for production of biocrude oil with higher conversion rates than the carbohydrates fraction. This correlates with research from Vo et al. (2017), that biomass with a higher lipid content produces higher yields of biocrude oil.

Algae has the potential to produce the highest yield of biocrude attributed to its high energy density and lipid content (Vardona et al., 2011). The modelled reactions for the HTL reactor were formulated based on the literature and presented in Table 2. The conversion rates for each reaction were computed iteratively to replicate the results from the kinetic model (equations 6–11). It was found that with the HTL reaction at 300 °C and an algae flow rate of 10,000 kg h<sup>-1</sup> (14 wt% solids), biocrude oil production was 943.5 kg h<sup>-1</sup> which is equivalent to a yield of 46.35 wt% on a dry basis, which is similar to previous reports (Valdez et al., 2014). As food waste contains lower lipid content than algae, it is expected that the biocrude yield would be lower, in this case, 39.33 wt% (dry basis) was found. Likewise, sewage sludge feedstock results in a biocrude yield of 43.93 wt%.

### 2.5.2. Modelling the biocrude upgrading process

The biocrude upgrading (hydrotreating) process was modelled using an RStoic reactor in Aspen Plus. The process operates at a temperature of 400 °C and a pressure of approximately 100 bar. Excess hydrogen, compared to the stoichiometric requirement, was used in the hydrotreating process and the amount of consumption was estimated using a heuristic value of 0.05 kg of H<sub>2</sub> per kg of biocrude upgraded (Bai et al., 2014). To the same effect, it was estimated that 4.5 kg of wastewater per 100 kg of biocrude was generated (Snowden-Swan et al., 2017). For the conceptual model in this study, this corresponds to a hydrogen consumption of 47.2 kg h<sup>-1</sup> and 42.5 kg h<sup>-1</sup> of wastewater discharge. The upgrading reaction involves the elimination of oxygen in the organic compounds using a simplified hydrotreating model. A conversion of 100% was assumed for each reaction (Tzanetis et al., 2017).

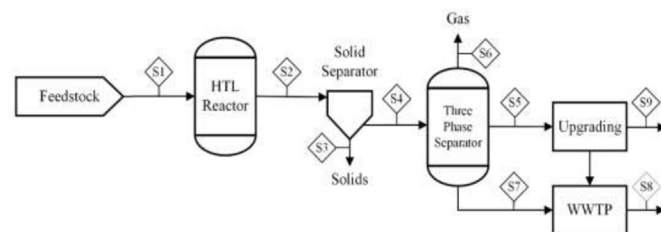


Fig. 3. Simplified Flow Diagram of the Base case of the HTL Plant.

## 2.6. HTL system configurations

### 2.6.1. Base case without heat integration

A simplified flow diagram of the HTL base case model is illustrated in Fig. 3. A slurry feed of biomass (S1) of 10,000 kg h<sup>-1</sup> with 15–25% solids was initially set at 200 bar and heated to 300 °C before flowing into the HTL reactor. The HTL reactor converts the biomass into an organic biocrude phase, an aqueous phase, a gaseous phase and a solid char fraction. The product from the HTL reactor (S2) is then fed to a cyclone where the solids stream (S3) of 220 kg h<sup>-1</sup> is removed from the process. It has been assumed that the solids phase is removed without resource recovery in this case.

The remaining mixture (S4) is cooled to 60 °C before entering a three-phase separator which separates the biocrude (S5), gaseous phase (S6) and AP (S7) into individual fractions with flowrates of 820 kg h<sup>-1</sup>, 150 kg h<sup>-1</sup> and 8810 kg h<sup>-1</sup>. The AP (S7) is treated in WWTP consisting of an ammonia stripper and a lime softening unit before being sent to headworks (S8). The biocrude fraction (S5) is sent to upgrading which occurs at 100 bar and 400 °C. Upgrading is necessary to remove oxygen, nitrogen and sulphur content from the biocrude to meet the fuel specifications. The upgrading is essentially a catalytic hydrotreating process which utilises NiMo/Al<sub>2</sub>O<sub>3</sub> as a catalyst (Castello et al., 2019) and requires an external input of hydrogen. In the hydrotreating process the oxygen content from the biocrude is converted to water and the nitrogen to ammonia (Snowden-Swan et al., 2017). The resulting refined product (S9) consists of a mixture of aromatic and aliphatic hydrocarbons that falls within the gasoline, jet and diesel ranges. A mass balance for the process is presented in Table 3. The heating and cooling requirements for the base case were estimated from the Aspen Plus model and amount to 3.35 MW and 4.15 MW.

### 2.6.2. Case 1 – base case with heat integration

Heat integration using pinch analysis was performed on the HTL system in view of attaining optimum energy recovery and thereby minimising utility (i.e. steam and cooling water) consumption (Towler and Sinnott, 2019). The minimum temperature approach ( $\Delta T_{min}$ ) for heat exchange was assumed to be 10 °C and the pinch point was found to be at 300 °C. The minimum heating and cooling requirements were found to be 120 kW and 920 kW. Through heat integration there is a 96.4% and 77.8% decrease in heating and cooling utility compared to the base case

Table 2  
Modelled Reactions for the HTL reactor.

Ref	Reaction number	Reaction	Stoichiometric Reaction	Conversion Rate (%)
Raza (2014)	1	Triolein + Water → Oleic acid + Glycerol	$C_{57}H_{104}O_6 + 3H_2O \rightarrow 3C_{18}H_{34}O_2 + C_3H_8O_3$	100
Toor et al. (2011)	2a	Glucose → Furfuraldehyde + Formaldehyde + Water	$C_6H_{12}O_6 \rightarrow C_5H_4O_2 + CH_2O + 3H_2O$	80
Toor et al. (2011)	2b	Glucose → Glyceraldehyde	$C_6H_{12}O_6 \rightarrow 2C_3H_6O_3$	85
Toor et al. (2011)	2c	Glucose → Benzenetriol + Water	$C_6H_{12}O_6 \rightarrow C_6H_6O_3 + 3H_2O$	85
Toor et al. (2011)	2d	Glucose → Acetic acid + Erythrose	$C_6H_{12}O_6 \rightarrow C_2H_4O_2 + C_4H_8O_4$	90
Raza (2014)	3	Valine → Propane + Ammonia + Carbon Monoxide	$C_5H_{11}NO_2 \rightarrow C_3H_8 + NH_3 + 2CO$	60
Raza (2014)	4	Alanine + Water → Lactic acid + Ammonia	$C_3H_7NO_2 + H_2O \rightarrow C_3H_6O_3 + NH_3$	60
Raza (2014)	5	Lactic acid → Acetaldehyde + Carbon Dioxide + Hydrogen	$C_3H_6O_3 \rightarrow C_2H_4O + CO_2 + H_2$	20
Raza (2014)	6	Glycerol + Water → Methanol + Carbon Dioxide + Hydrogen	$C_3H_8O_3 + H_2O \rightarrow CH_3OH + CO_2 + H_2$	20
Raza (2014)	7	Leucine → Pyrrole + Methane + Carbon Dioxide + Hydrogen	$C_6H_{13}NO_2 \rightarrow C_4H_5N + CH_4 + CO_2 + 2H_2$	80
Raza (2014)	8	Serine + Water → Formic Acid + Methylamine	$C_3H_7NO_3 + H_2O \rightarrow 2CH_2O_2 + CH_3NH_2$	80

**Table 3**  
Mass balance of HTL plant.

Component mass flow (kg h <sup>-1</sup> )	Stream							
	S1	S2	S3	S4	S5	S6	S7	S9
Mass Flows (Total)	10000	10000	218.4	9781.6	822.4	150.6	8808.7	866.0
Water	8600	8534.5	0	8534.5	0	0	8534.5	158.8
Triolein	805	80.5	80.5	0	0	0	0	0
Glucose	81.2	2.1	2.1	0	0	0	0	0
Valine	105	10.5	10.5	0	0	0	0	0
Alanine	105	10.5	10.5	0	0	0	0	0
Leucine	105	10.5	10.5	0	0	0	0	0
Serine	105	10.5	10.5	0	0	0	0	0
Oleic acid	0	693.4	0	693.4	693.4	0	0	0
Glycerol	0	60.3	0	60.3	0	6.0	54.3	0
Formaldehyde	0	45.2	0	45.2	0	44.7	0.5	0
Propane	0	35.6	0	35.6	0	35.6	0	43.2
Ammonia	0	31.8	0	31.8	0	0.3	31.5	0
Lactic acid	0	76.4	0	76.4	68.8	0	7.6	0
Acetic acid	0	9.3	0	9.3	0	0	9.3	0
Carbon monoxide	0	48.2	0	48.2	0	48.2	0	0
Hydrogen	0	3.7	0	3.7	0	3.7	0	17.0
Methanol	0	10.5	0	10.5	0	0	10.5	0
Pyrrole	0	48.3	0	48.3	0	0	48.3	0
Methane	0	11.6	0	11.6	0	11.6	0	0
Formic acid	0	82.8	0	82.8	0.4	0.4	81.9	0.4
Methylamine	0	27.9	0	27.9	0	0.0	27.9	0
Benzenetriol	0	34.1	0	34.1	34.1	0	0	0
Furaldehyde	0	4.2	0	4.2	4.2	0	0	0
Formaldehyde	0	1.3	0	1.3	0	0	1.3	0
Glyceraldehyde	0	19.5	0	19.5	19.5	0	0	0
Erythrose	0	2.1	0	2.1	2.1	0	0	0
Acetaldehyde	0	1.0	0	1.0	0	0	1.0	0
Octadecene	0	0	0	0	0	0	0	619.8
Cyclohexane	0	0	0	0	0	0	0	22.8
Cyclopentane	0	0	0	0	0	0	0	3.0
Butane	0	0	0	0	0	0	0	1.0
Ash	93.8	93.8	93.8	0	0	0	0	0

which has heating and cooling requirements of 3.35 MW and 4.15 MW.

### 2.6.3. HTL with heat integration and resource recovery (case 2)

In the base case it was assumed that the AP effluent from the HTL reactor was sent to WWTP before being discharged to the environment. In this case, the organic content in the AP fraction was recovered using CHG into hydrogen for use in upgrading. By assuming 0.15 gram of H<sub>2</sub> production per gram of biocrude upgraded (Cherad et al., 2016), hydrogen produced by CHG was estimated to be 141 kg h<sup>-1</sup>, which is much greater than the hydrogen requirements for upgrading estimated in Section 2.3.2 (47.2 kg h<sup>-1</sup>) by using reaction stoichiometry. This creates a surplus of hydrogen of 93.8 kg h<sup>-1</sup> whilst eliminating the need for purchasing external-sourced hydrogen for upgrading, hence bringing significant economic and environmental benefits.

The CHG reactor operates a temperature of 374 °C and there is opportunity for heat recovery from the reactor outlet stream. By performing pinch analysis, it was found that the pinch point occurred at 305 °C, resulting in minimum heating and cooling requirements of 0.18 MW and 1.69 MW. This corresponds to a 94.6% reduction in heating utility and a 59.3% reduction in heating utility compared to the base case. Table 4 summarises the difference in heating and cooling duties between the different cases.

Energy can be recovered by combusting the gaseous and solid phase

**Table 4**  
Comparison of Heating and Cooling duties for the different cases of HTL plant.

Case		Heating Duty (MW)	% Reduction	Cooling Duty (MW)	% Reduction
1)	Base Case	3.35	–	4.15	–
2)	Case 1	0.12	96.4	0.92	77.8
3)	Case 2	0.18	94.6	1.69	59.3

reactor effluents. The remaining fraction of the solid char was determined to have a relatively high heating value (15.7 MJ kg<sup>-1</sup>) which can be combusted in a furnace to generate steam to help reduce the heating utility requirements of the plant. It was assumed that the furnace has a thermal efficiency of 47.2% (Anastasakis and Ross, 2015) and can thus provide 410 kW of additional heating. The gaseous phase was calculated to have a lower heating value, similar to that of biogas, of 17.8 MJ kg<sup>-1</sup> which provides 217 kW of heating utility (Jalalzadeh-Azar et al., 2010) when assuming a thermal efficiency of 47.2% for the combustion process. The total heating utility requirement of Case 2 using heat recovered from the gaseous and solid streams decreased by 63%. Additionally, zinc and iron, which can potentially be recovered by up to 7.3% and 3% from the solid phase (Raikova et al., 2016) (if algae is cultivated in former mining plants), can be separated and sold to improve the economic performance of the plant at 600 £ t<sup>-1</sup> (Tzanetis et al., 2017).

## 3. Results and discussion

### 3.1. Economic assessment

The plant with a feed throughput of 10,000 kg h<sup>-1</sup> was designed to operate for 8000 h per year, assuming a plant life of 30 years. The capital and operating costs as well as the MFSP are presented in Table 5. The total capital costs were calculated at approximately 11.6 million £ for the base case of the HTL plant using algae feedstock. For the use of sewage sludge, additional dewatering of the feedstock is required on site to eliminate challenges in transporting wet sludge to external facilities, and hence the total capital costs are estimated to be 12.7 million £.

The fixed operating costs were calculated based on the costs of employment, overheads and maintenance capital and the variable operating costs were calculated based on the cost of the feedstock, hydrogen input, catalyst and wastewater treatment. For algae, most of

**Table 5**

Capital and operating costs and the MFSP for each HTL case and the potential to fulfil UK demand of SAF.

Item	Base Case	Case 1	Case 2		
	Algae	Algae	Algae	Food Waste	Sewage Sludge
Biocrude Production (million $l\ y^{-1}$ )	9.8	9.8	9.8	5.5	9.7
Capital Costs (million £)	11.6	11.1	12.7	10.9	12.9
Operating Costs (million £ $y^{-1}$ )	7.2	6.8	6.2	2.7	3.0
MFSP (£ $l^{-1}$ )	0.86	0.81	0.77	0.70	0.50
UK Resource Availability <sup>a</sup> (Mt $y^{-1}$ )	–	–	7.18 <sup>b</sup>	10.0 <sup>c</sup>	6.00 <sup>d</sup>
Potential of SAF production (Mt fuel $y^{-1}$ )	–	–	1.01	1.14	0.78
Percentage of demand based on a targeted SAF demand of 12.8 Mt in the UK (%)	–	–	7.89	8.88	6.06
Number of plants required	–	–	90	125	75

a) Wet Weight b) POST (2011) c) House of Commons (2017) d) Trust in Water (2020)

the variable operating costs arise from the feedstock where mass cultivation of algae utilising economies of scale is still in the research phase causing current costs of algae to remain relatively high (POST 2011). Quicklime used for AP treatment also accounts for a significant fraction of variable operating costs which results in a large decrease in operating costs for Case 2 which does not include WWTP due to the AP fraction being treated with CHG. The lower operating costs in Case 1 is a result of using heat recovery methods.

With the adoption of recovery strategy using CHG in Case 2, in the case of the algal feedstock, the MFSP decreased by 10.5% compared to the base case. The MFSP for the use of food waste and sewage sludge as feedstock for Case 2 was lower than for algae by 9.1% and 35.1%. The difference is attributed primarily to feedstock price, although there are other factors including the yield of biocrude and difference in capital costs, for instance, the requirement for sludge dewatering. The use of sewage sludge in an HTL plant with heat integration and resource recovery has the lowest MFSP of 0.50 £  $l^{-1}$  due to the high yield and low price of feedstock. The economic assessment in this study has shown that the price of fuel produced by HTL ranges from 0.50 to 0.76 £  $l^{-1}$  depending on the feedstock which is similar to the value of 0.59 £  $l^{-1}$  found by Snowden-Swan et al. (2017). This is significantly more expensive than the price of petroleum-based jet fuel, 0.16 £  $l^{-1}$  (IATA, 2015).

A sensitivity analysis on Case 2 with resource recovery using sewage sludge feedstock (the best performed scenarios based on the economic assessment shown in Table 5) was conducted to investigate how the MFSP varied with respect to some of the assumptions and is illustrated in Fig. 4. The yield of biocrude has significant effect on the MFSP. A lower yield of biocrude could result in a large increase in MFSP, i.e. a 20% decrease in yield corresponds to a 25% increase in MFSP. A 25% increase in feedstock costs results in an 18% increase in MFSP. Reducing the price of feedstock is vital in improving the economic performance of the HTL plant. A 50% increase in capital costs results in a 4.4% increase in MFSP. Increasing the plant life from 30 to 40 years has a minor effect on MFSP (only a 1.5% decrease). Additionally, the MFSP increases by 25% when the throughput is reduced to 5000 kg  $h^{-1}$  whilst the MFSP decreases by 28% when the throughput is increased to 100,000 kg  $h^{-1}$ . A larger throughput is recommended to benefit from economies of scale. It was also found that an increase of internal rate of return from 10% to 15% results in an 8% increase in MFSP.

### 3.2. Regional resource assessment

A regional resource assessment was conducted to examine the biocrude production potential in different regions in the UK and identify suitable locations for establishing HTL plants. The availability of feedstock in each region was converted into biocrude production potential for each region by multiplying the biocrude yield obtained from modelling. The yield of jet fuel from the upgraded biocrude produced by the HTL plant was assumed to be 28.4% (Tzanetis et al., 2017). The number of plants required was calculated based on the plant specifications modelled in this study (i.e. feed flow rate of 10,000 kg  $h^{-1}$  for 8000 h  $y^{-1}$ ). Table 5 summarises the availability of the organic feedstock (algae, food waste and sewage sludge) and outlines the potential to fulfil UK jet fuel demands with a SAF demand of 12.8 Mt of jet fuel per year in the UK (IEA, 2019).

It was found that a maximum of 22.8% of the current UK jet fuel requirements can be met with HTL technology if all available organic resources (i.e. algae, food waste and sewage sludge) were fully exploited. This would require a total of 290 plants, and it is an overestimate as competing uses for the feedstock and adoption of other technologies have not been studied exhaustively. Further evaluation would be needed to fully understand the economic and practical feasibility of establishing such a large number of plants in the UK. The result is comparable to the research by Skaggs et al. (2018) who found that 23.9% of the US aviation fuel demand could be met by utilising waste feedstocks. GIS mapping was performed to obtain an estimation of biocrude production potential in

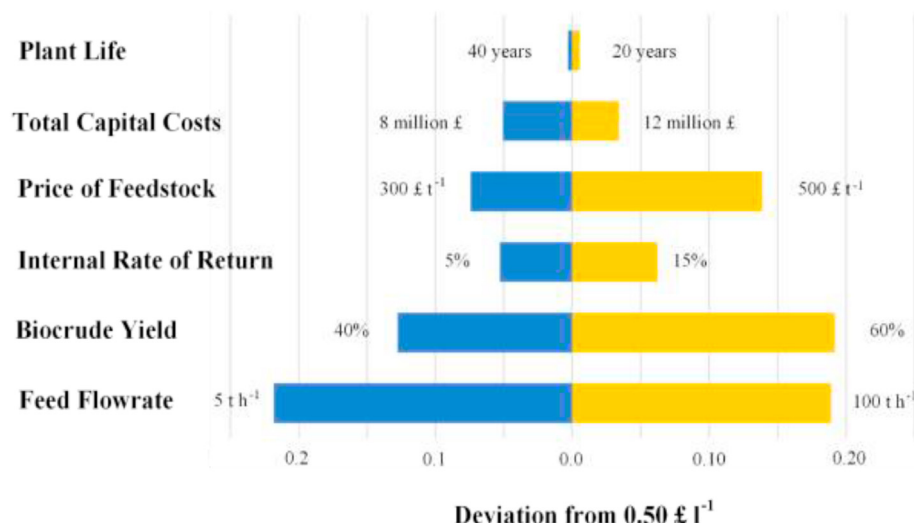


Fig. 4. Sensitivity analysis based on Case 2(c) with sewage sludge feedstock.

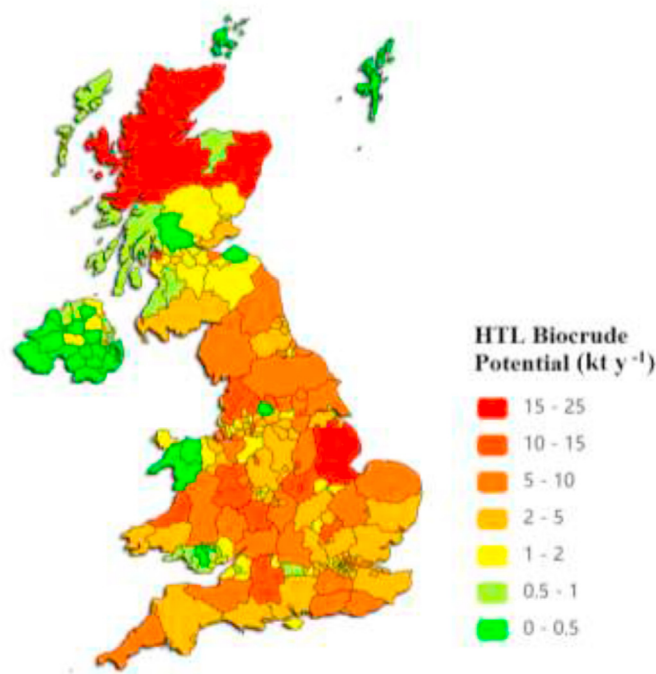


Fig. 5. GIS map for the UK indicating the biocrude production potential from HTL plants utilising localised organic waste feedstock including food waste and sewage sludge.

different regions in the UK which is displayed in Fig. 5. Algae is not included in this study as data and regional studies for future cultivation are scarce.

The regional resource analysis shows that most regions in the UK, except for the majority of Northern Ireland, are able to produce a minimum of  $2 \text{ kt y}^{-1}$  of biocrude (jet fuel fraction) to sustain a potential HTL plant with the same throughput as the conceptual plant modelled in this study. It was found that regions in Scotland (Aberdeen and Highlands) are favourable locations to establish HTL plants attributed to the high density of biocrude production potential. This is due to a large quantity of food waste accumulated in landfills in the Highlands (DEFRA, 2008). It must be considered that there are very few airports in Scotland and hence transportation is required over large distances which would lead to adverse environmental effects. Ceredigion in West Wales is an attractive region with high biocrude potential and it is in the vicinity of Aberporth Airport. Lincolnshire and Norfolk in the East Midlands are also promising for a plant with high biocrude production potential close to Robin Hood Airport.

The potential of establishing HTL in London deserves further study due to the concentration of the population and the number of airports in the region. Albeit many counties surrounding London are shown to be good potential locations with not only the huge demand and proximity of London airports but also, with large populations that generate sufficient waste to be used as feedstock to sustain plants. This study has positioned landfills and WWTP's as the sources of feedstock for steady integration into existing supply chains for food waste and sludge disposal. If the HTL process technology is to grow it may be able to establish its own new supply chains for distribution which will alter the GIS map significantly. The potential of SAF production is an overestimate as it assumed that all the available feedstock in each region will be able to be sustainably transported to potential HTL plants.

### 3.3. Carbon footprint assessment

A carbon footprint assessment was conducted based on the Greenhouse Gas Protocol (2015) to examine the environmental impact of the

HTL plant in Case 2. The aim of the carbon footprint assessment is to compare the  $\text{CO}_2$  emissions across the lifecycle of the integrated HTL production process against conventional petroleum-based kerosene aviation fuel. The assessment was conducted from cradle-to-grave, from the collection/growth of feedstock to the combustion of the fuel in jet engines.

The GHG emissions for each part of the production process, illustrated in Fig. 6(a), were calculated using specific GHG emission factors. The specific GHG emission factors for the growth of algae feedstock and the avoided emissions from food waste disposal in landfills and sewage sludge processing in WWTP have also been included. The combustion of the fuel in the jet engines is not included as a process in Fig. 6(a). The emissions from the CHG reactor was shown to have the highest contribution to GHG emissions during production. The average distance of transportation of feedstock used for calculation of emissions was estimated by measuring the distance between each region in Section 3.2 to the closest airport and is calculated to be 44.3 km. Equation (5) was used to calculate the total GHG emissions using the emission factors for different jet fuel, illustrated in Fig. 6(b).

As shown in Fig. 6(b), algae based jet fuel has a total GHG emissions of  $0.38 \text{ kg CO}_2 \text{ kg}^{-1}$  of aviation fuel which is an 89.5% reduction in emissions in comparison to petroleum-based kerosene fuel. Sewage sludge based jet fuel has a reduction of 99.6% in comparison to conventional fuel and was found to be the most environmentally attractive feedstock for production of jet fuel with HTL. Food waste based jet fuel has a 58.7% reduction in emissions in comparison to conventional jet fuel which gives the lowest reduction in emissions between the three feedstocks. This is due to avoided emissions from food waste disposal in landfill sites being much lower than the combustion of the jet fuels in jet engines resulting in a lower carbon neutrality. With a maximum production of  $2.93 \text{ Mt y}^{-1}$  of jet fuel from Section 3.2, there is an aggregated saving of emissions of 18.3% across the UK jet fuel aviation industry which could play an important role in climate change mitigation.

## 4. Conclusions

Producing sustainable aviation fuel from carbon-neutral feedstock such as algae, food waste or sewage sludge using the HTL process has the potential to reduce carbon emissions in the aviation industry. The process requires further development to improve the economic performance and reduce GHG emissions. There is also a need to assess the availability of feedstock and the potential of the technology in areas such as the UK to build investor confidence. This study investigated how an integrated HTL plant incorporating heat integration and resource recovery from waste could potentially improve the economic performance and reduce GHG emissions for jet fuel production in the UK. Heat integration has eliminated the need for external heating by steam and reduced the carbon emissions of the plant. Sewage sludge based jet fuel has the lowest overall GHG emissions and the lowest MFSP in comparison to when algae and food waste are used as feedstock. The sensitivity study on the minimum fuel selling price revealed that the yield of biocrude of the reactor, the cost of feedstock and the size of the plant have a large effect on the MFSP and need to be considered carefully. The regional assessment demonstrated that nearly a quarter of the UK jet fuel demand can be met with integrated HTL technology utilising locally available organic resources. This research can be repeated on different regions and countries to study their specific challenges in more detail. Potential areas for future research include (i) evaluating the feasibility of integrated plant configurations with lab-scale and pilot studies to further validate results from conceptual studies; (ii) characterising the composition of reactor effluent streams to examine the viability of resource recovery strategies; and (iii) validating HTL reaction kinetics and determining the effect of reaction conditions on the yield of biocrude.

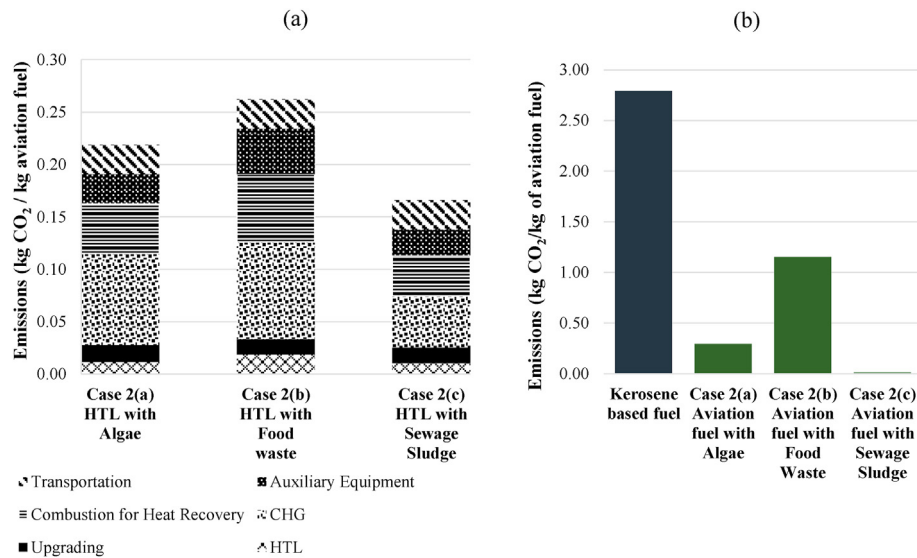


Fig. 6. (a) GHG emissions attributed to production of jet fuel using different feedstock; (b) Total GHG emissions for each case.

### CRedit authorship contribution statement

**Danial Farooq:** Conceptualization, Methodology, Validation, Investigation, Formal analysis, Visualization, Writing - original draft. **Ian Thompson:** Validation, Writing - review & editing. **Kok Siew Ng:** Conceptualization, Supervision, Validation, Writing - review & editing.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supplementary data

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