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Determination of Carbon Footprint using LCA Method for Straight Used Cooking Oil as a Fuel in HGVs

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Abstract

In order to improve energy supply diversity and reduce carbon dioxide emissions, sustainable bio-fuels are strongly supported by EU and other governments in the world. While the feedstock of biofuels has caused a debate on the issue of sustainability, the used cooking oil (UCO) has become a preferred feedstock for biodiesel manufacturers. However, intensive energy consumption in the trans-esterification process during the UCO biodiesel production has significantly compromised the carbon reduction potentials and increased the cost of the UCO biodiesel. Moreover, the yield of biodiesel is only ~90% and the remaining ~10% feedstock is wasted as by-product glycerol. Direct use of UCO in diesel engines is a way to maximize its carbon saving potentials. This paper, as part of the EPID (Environmental and Performance Impact of Direct use of used cooking oil in 44 tonne trucks under real world driving conditions) project, presents the life cycle analysis of Straight UCO (SUCO) in terms of CO_2 and energy consumption, compared with the UCO biodiesel and petroleum diesel. The UK carbon calculator developed by UK Department for Transport was used for the calculations. The results show that SUCO renewable fuel can reduce the WTW carbon footprint by 98% compared to diesel and by 52% compared to the UCO biodiesel.

Introduction

The ever increasing consumption of conventional fossil fuels has caused serious concerns on climate change and energy supply security issues. Transport sector is one of the major CO_2 producers, accounted for about a quarter of total CO_2 emissions globally. Among the transport CO_2 emissions, road transport dominated the total transport CO_2 emissions. The UK Vehicle Certification Agency (VCA) reported that 90% of all transport GHG emissions from road transport [1]. Biofuels as a means to reduce road transport carbon footprint have attracted great attentions during the last decade.

Biodiesel is one of the major biofuels in Europe. The application of biodiesels in diesel engines is a relatively mature technology in terms of production and combustion in diesel engines. In general, biodiesel can burn well in diesel engines and produces lower CO, hydrocarbon and particular matter (PM) emissions compared to petroleum diesel [2-8]. However, has the biodiesel delivered its main objective-carbon reduction and by how much compared to petroleum diesel? The answer will vary. The potential of carbon reduction by biodiesels will depend on feedstock and production processes but the feedstock is a key parameter [9]. Currently biodiesels produced in the EU are mainly using edible vegetable oils as feedstock such as rape seed oil [10, 11]. These biodiesels (first generation) are often the topics of public debates due to their effects on rising food price and ethical issues such as starvation in developing countries and the competition between land use for cultivation of oilseeds as feedstocks for bio-diesel manufacture, and land use for cultivation of food crops. The second generation of biodiesels uses non-edible biomass such as lignocellulos as the feedstock but the cost of the production process is high and not economically viable at present. Thus the attention has been diverted to using the Used/Waste Cooking Oil (UCO or WCO) as a feedstock to produce biodiesels [9, 12], which is much easier to be accepted by public with regard to moral aspects and more economically viable. In the UK, UCO's contributions to total biodiesel productions reached 66% in 2012-13 [13].

However, converting UCO into biodiesel involves trans-esterification process, in which the carbon footprint of methanol is brought into the fuel chain. This factor along with the demand for extra energy for the process and a typical yield of 90% reduces the carbon reduction potential of UCO biodiesel. Esteban et al [14] assessed the advantages of use SVO (Straight Vegetable Oil) directly as biofuel versus biodiesel and showed a clear preference for SVO compared to biodiesel. Peiró et al [15] conducted a LCA (Life Cycle Analysis) assessment for a used cooking oil based biodiesel and found that the transesterification stage accounted for 68% of the total environmental impact.

To maximize the carbon reduction potential of UCO, the EPID project is set up to examine and investigate the environmental and performance impact of direct use of Straight UCO (SUCO) in diesel engine powered 44 ton trucks. Ten trucks have been converted to be able to burn the SUCO fuel with an on-board blending system-Bioltec system. A dual fuel tank containing SUCO and petroleum diesel has been fitted to each truck. The Bioltec blending system is a microcomputer controlled automatic fuel selection and blending system, which can select fuel supply (diesel or SUCO) and adjust blending ratio based on certain measured engine operational parameters such as fuel temperature and load [16]. Fuel consumption, engine deposits, exhaust emissions, lube oil aging and operational performance have been monitored. This paper, as part of the project, assessed the WTW (Well To Wheel) CO_2 emission for SUCO using the LCA method.

One of the major benefits for the SUCO fuel is the increased carbon reduction potential compared to the UCO biodiesel. This will not only be beneficial globally but also can improve companies' images and reputations on carbon footprint. This is particularly suitable for the catering and food sector as they may utilize their own waste cooking oils to produce energy/fuels for processes and/or drive their own vehicles. Other benefits of SUCO renewable fuels include its transportability (easy and safer to transport, compared with diesel), biodegradability, local accessibility, recyclability, no or trivial aromatic and sulphur contents, and eco-friendliness [17].

Methodology

Define the goal and scope

The goal of this work was to determine WTW energy consumption and carbon footprint (CO_2e) of SUCO renewable fuel in the UK using the Life Cycle Analysis (LCA) method. As the TTW (Tank To Wheel) carbon footprint of SUCO is zero, i.e. zero CO_2 emissions from tailpipe by SUCO are deemed because emitted CO_2 from tail pipe will be absorbed by plants during their growth. Therefore the WTW carbon footprint analysis of SUCO is equivalent to its WTT carbon footprint results. The scope of the system used in this paper included the raw UCO transportation after collection, factory processing stages and transportation and dispensing of the finished products. The energy consumption and carbon footprint for each stage was calculated based on the production of one ton of the finished SUCO renewable fuel. The total carbon emission was calculated and compared with UCO biodiesel and diesel.

LCA flow chart, functional unit and system boundary

Appendix A presents the production process of the SUCO renewable fuel and its system boundary. The functional unit is $kgCO_2$ equivalent emitted for the production of one ton of the SUCO renewable fuel and gCO_2 equivalent emissions for one MJ of energy from the SUCO fuel. As shown in appendix A, there are four stages in the LCA, which are transportation and loading off, refining, delivering and fuel dispensing. The energy consumption of the refining stage is divided into three sections: pumps, heating and compressor for the transfer of UCO between vessels, internal flows within vessels, heating UCO and providing compressed air etc.

Inventory analysis

The inventory analysis has focused on energy consumption (MJ/ton) and carbon emission ($kgCO_2e$/ton and gCO_2e/MJ). Electricity and diesel were the main energy sources consumed during the UCO refining.

Definition of the reference systems

The UCO derived biodiesel and petroleum diesel were taken as the reference systems during the whole LCA of the SUCO renewable fuel. The UCO biodiesel was used a reference system as it had the same feedstock as the SUCO but with different processing pathways. Petroleum diesel was the ultimate target for the determination of carbon reduction potentials of the SUCO. Typical values for the carbon footprint of petroleum diesel from literature were used.

The location for the LCA analysis was based in the UK. The time of the analysis was between 2012 and 2013, which meant that the electricity and diesel emission factors were taken from the UK during 2012 to 2013 as references. The emission factor was 0.128 $kgCO_2e$/MJ for electricity and 0.0876 $kgCO_2e$/MJ for diesel.

UK carbon calculator

The UK carbon calculator is a software package for carbon emission calculation for any fuels. Under the requirement of Renewable Transport Fuels Obligation (RTFO), Life Cycle Analysis (LCA) methodology is a normalized carbon calculator in the UK to quantify the carbon emission for bio-fuels production [18]. The software provides not only readily available standard fuel chains like biodiesel fuel chain containing standard production stages or modules using standard values but also has flexibilities for modifying individual stages or modules for particular cases such as adding extra stages or deleting some stages. The type of the feedstock can be selected. The production processes could be edited within the software to meet individual requirement. It could generate reports by monthly or yearly and calculate the carbon emissions for each step or module of the whole fuel production chain. An example of the graphic representation of a fuel chain is shown in figure 2 for the UCO biodiesel production.

Results and discussions

Energy consumption during SUCO renewable fuel production

The transportation of the raw UCO and its loading off was the first stage within the LCA boundary. The raw UCO was collected from factories in Manchester and Rotherham and delivered to the biofuel refining factory. The distances from these two collection points were different and the amount of raw UCO was also different as shown in Table 1. Based on the share of the amount of the raw UCO transported, an average distance of 70km was obtained. 10-ton diesel trucks were used as a means of transportation of the raw UCO.

Table 1: Distance for the transportation of raw UCO

Collection point	**Distance**	**Percentage**
Manchester	45 km	64%
Rotherham	114 km	36%
Average distance	70 km	

Table 2 shows the energy consumption of each stage of the SUCO production which were derived from the measured data by manufacturer. It can be seen that the heating loads were the most energy intensive process consuming a large amount of electricity by a pump, a heater and an air compressor. The transportation of the finished SUCO fuel to the fleet was the second largest energy consuming module. Electricity was the dominant form of the energy required for the production of the SUCO fuel.

Table 2: Energy consumption (Unit: MJ/ton)

Process	Consumer	Energy type	Amount (MJ/ton)
Transportation and loading off	Road tanker and Tanker PTO	Diesel	84
Refining process	Heating loads	Electricity	202.2
	Pump loads	Electricity	31.86
	Compressor loads	Electricity	108
Transportation of finished SUCO	Road Tanker and Tanker PTO	Diesel	141.26
Fuel dispensing	Heater	Electricity	39
Total			***606.32***

Carbon emissions for SUCO renewable fuel production

The carbon emissions in the six stages/phases of the production of the SUCO renewable fuel were calculated by the UK carbon calculator and are presented in Table 3 in terms of $kgCO_2e$ per ton of SUCO fuel. The results are also converted to fractions of CO_2e emissions for each stage/phase as shown in Figure 1.

From Table 3 and Figure 1, it is observed that the largest carbon emissions were from the heating loads of the refining process, accounted for more than a third of the total SUCO CO_2 emissions. The heating was provided by electric heaters. It is possible to reduce carbon emissions if the industrial compressed air was used and the heating sources from other industrial processes could be used, especially waste heat. It is also possible to reduce carbon emissions from the refining process using a combined heat and power (CHP) unit burning SUCO fuel so that the electricity can be used to drive compressor and transfer pumps and the heat from CHP can be used to heat the UCO. The process itself could also be further optimized such as more efficient heater and shorter heating time etc.

The second largest carbon emission source was from pumps for circulating and transferring the UCO with a share of 21%. The third largest carbon emission source was SUCO product transportation, accounted for 16%. The way to reduce carbon emissions for this stage was localization, i.e. set up the refinery factory close to end users.

Table 3: Carbon emissions for SUCO fuel production

Modules	Carbon emission ($kgCO_2e/ton$)
Transportation of raw UCO and loading off	7.41
Refining Process-heating	26.42
Refining Process-compressor	4.16
Refining Process-pump	14.11
Transportation of finished SUCO fuel	11.2
Fuel dispensing	5.42
Whole fuel chain	***68.73***
Whole fuel chain carbon intensity (gCO_2e/MJ)	***1.76***

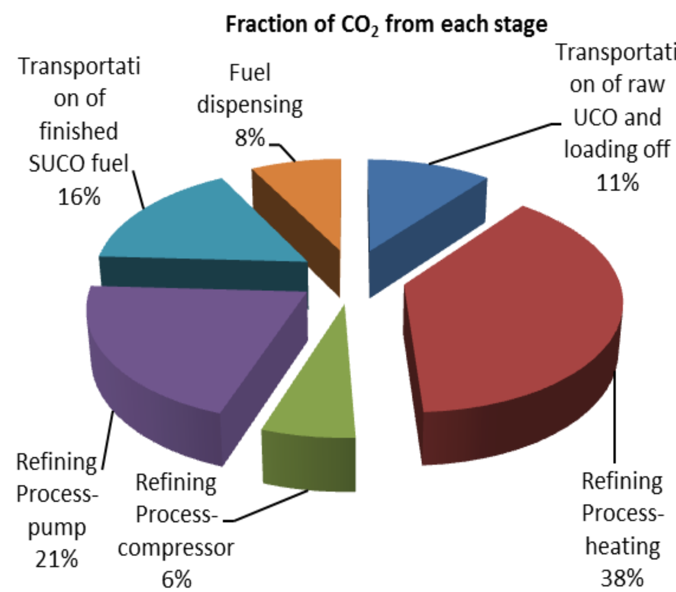

Figure 1: Fractions of CO_2e emissions for each stage of SUCO renewable fuel production

Carbon emission for biodiesel production

The carbon footprint of UCO biodiesel, as a reference to SUCO, was determined by using the same carbon calculator. The type of the feedstock and transportation distance were set as the same as the SUCO renewable fuel for biodiesel production, i.e. the feedstock of biodiesel was set as UCO and the transportation distance was 70km for raw feedstock and 126km for biodiesel. Figure 2 presents the fuel chain of UCO biodiesel production generated from the UK DfT carbon calculator.

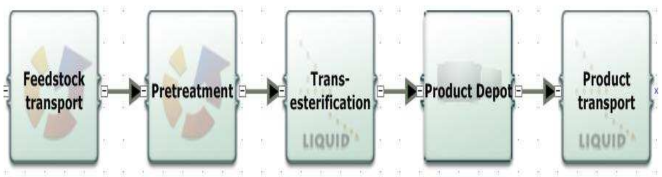

Figure 2: UCO biodiesel production chain obtained from UK DfT carbon calculator

Table 4 shows the carbon emissions of the biodiesel production from UCO. Figure 3 shows the percentage counting for total carbon emissions. The results in Table 4 and Figure 3 demonstrated that the trans-esterification process was the largest contributor for the carbon emissions, accounted for 58% of the total UCO biodiesel carbon emissions. The value for the carbon footprint of the trans-esterification process was chosen from default value of the carbon calculator model. Therefore this is a nationally recognized standard value. The value for the carbon footprint of the pretreatment of feedstock UCO was also taken from the default value of the model. It can be seen that the pretreatment was the second largest contributor to overall UCO biodiesel carbon emissions with a share of 26%. The carbon emissions for the transportation of the finished product (biodiesel) were the same as the SUCO because the distance was the same (126km) and the mass was the same (1 ton of finished product). The carbon emissions for the transportation of feedstock for biodiesel was slightly higher than that for the SUCO as the yield of biodiesel was lower (~90%) than the SUCO.

The calorific values of SUCO and biodiesel used in the calculation were ~39 MJ/kg, which was measured in the lab using the bomb calorimeter. The calorific value of diesel used in the calculation was 43 MJ/kg.

By comparison of the fuel chain carbon intensity between the SUCO renewable fuel in table 3 and the UCO biodiesel in table 4, it can be seen that the UCO biodiesel has twice as high as the SUCO carbon intensities, attributed to the trans-esterification process.

Table 4: Carbon emissions of biodiesel production from UCO

Modules	**Carbon emission ($kgCO_2e/ton$)**
Feed stock transport	8
Pretreatment	38.4
Trans- esterification	85.2
Depot	5.38
Product transport	11.2
Whole fuel chain	***148.18***
Fuel chain carbon intensity (gCO_2e/MJ)	***3.80***

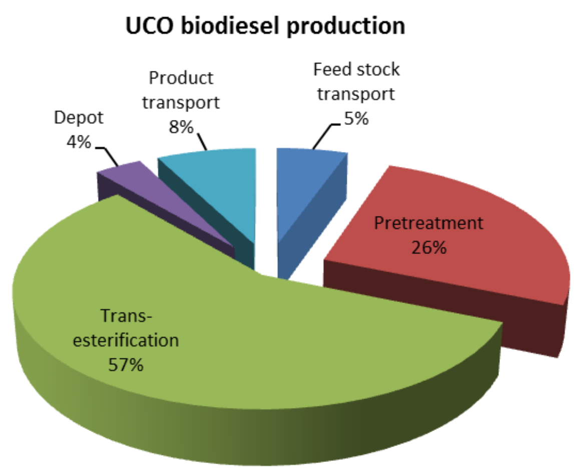

Figure 3: Relative contributions of each production stage to total CO_2e emissions for UCO biodiesel

Well to Wheel (WTW) carbon footprint and comparisons

The WTW carbon footprint includes the CO_2e emissions from WTT and TTW stages. The WTT CO_2e emissions for the SUCO fuel and UCO biodiesel have been calculated in previous sections. For petroleum diesel, the WTT carbon emission varies from different feedstock and different refining technologies [19]. A typical value of 15 gCO_2e/MJ was used for WTT carbon footprint of petroleum diesel in this paper. For TTW carbon emissions, it was deemed as zero for the SUCO and UCO biodiesel as the CO_2 from combustion of SUCO and UCO biodiesel were absorbed by plants during their growth, i.e. the carbon from the combustion of the SUCO and UCO biodiesel is already part of the global carbon cycle while the burning of petroleum diesel introduces new carbon emissions into the atmosphere. Thus, for the SUCO fuel and UCO biodiesel, WTW carbon emissions were equivalent to WTT emissions, while the WTW carbon emissions for diesel were the summation of WTT and TTW emissions. For diesel fuel, a standard value of 3100 gCO_2/kgfuel was used for its TTW emissions. The calorific value of diesel used was 43 MJ/kg. This gives a value of 72 gCO_2/MJ for the TTW carbon footprint of petroleum diesel.

The carbon produced during combustion phase considered here only contains CO_2. In theory, CO and unburnt hydrocarbons (UHC), and particulate matter (PM) due to incomplete combustion should be included in the carbon cycle as well. However, it is well known that the CO and UHC emissions from diesel are very low and negligible compared to CO_2. Li et al [20] measured CO and UHC emissions from a Perkins diesel engine using standard diesel and the pure vegetable oil as fuels and found that the CO and UHC emissions from the pure vegetable oil was similar to that of diesel. The magnitude of CO and UHC emissions was 0.1% of CO_2 emissions. Therefore, it is safe to say that CO and UHC emissions (combustion efficiencies) do not affect the WTW carbon footprint calculations of the SUCO. PM emissions from diesel engines are of a health concern but the amount of carbons contained is trivial compared to CO_2.

Figure 4 shows the comparison of whole life cycle carbon footprint for the SUCO renewable fuel, UCO biodiesel and diesel fuel. The value for the carbon footprint of diesel has employed the data from Biomass Energy Center [21]. The whole life cycle CO_2 equivalent emissions for the SUCO renewable fuel, biodiesel and diesel are 1.76 gCO_2e/MJ, 3.80 gCO_2e/MJ and 87 gCO_2e/ MJ respectively. A significant carbon saving from the UCO derived renewable fuel compared to diesel is clearly shown.

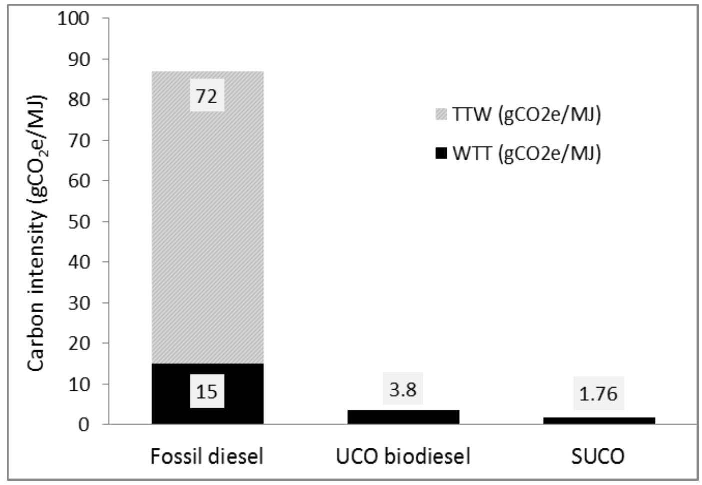

Figure 4: Comparison of carbon intensity between SUCO renewable fuel, UCO biodiesel and diesel

The LCA results show that the SUCO renewable fuel reduced carbon footprint by 54% compared to its counterpart UCO biodiesel and 98% compared to diesel. It is clear that the SUCO renewable fuel achieved carbon neutral target. The production of diesel fuel is not carbon intensive, but the CO_2 emissions from combustion are large. In contrast, the carbon emissions only happen during the fuel production and transportation period for the SUCO renewable fuel and biodiesel. It is this advantage that makes the SUCO a carbon neutral fuel.

As demonstrated, the reduced CO_2 emissions of the SUCO renewable fuel compared to the UCO biodiesel are due to the removal of the trans-esterification stage during the production process. The carbon emission of trans-esterification stage was nearly as the same as the whole carbon emission of the SUCO renewable fuel.

The UK Renewable Transport Fuel Obligation (RTFO) sets a mandatory request to fossil fuel suppliers that fossil fuel suppliers need to “produce evidence showing that a percentage of fuels for road transport supplied in the UK come from renewable sources and are sustainable, or that a substitute amount of money is paid. All fuel suppliers who supply at least 450,000 liters of fuel a year are obligated” [22]. Biodiesel, along with bioethanol, is one of the biofuels for industries to meet such requirement. This has set the two different diesel biofuel markets: one is biodiesel aiming to meet mandatory requirement and currently can be blended with fossil diesel up to 7%; the other is to target users who wish to lower the carbon footprint of their transport. Biodiesel currently is the dominant diesel biofuel product because of its compatibility with existing diesel engine technologies without a need to modify engines. However, the LCA results show that the carbon footprint from the SUCO fuel was lower than biodiesel from the same feedstock. It would require less amount of biofuel to meet the same carbon reduction target if part of the biodiesel market can be replaced by the SUCO renewable fuel. This is particularly important as the biofuel resources are limited.

The results from this research show that trans-esterification process would emit 85.2 $kgCO_2e$ per ton of the UCO biodiesel produced, which was larger than the carbon emission of the entire SUCO renewable fuel production process. Removal of trans-esterification process by the SUCO fuel production could save a significant amount of carbon emissions. It should be pointed out that the material and energy recycle of co-product from biodiesel production (glycerol) was not counted in the above calculations, which would reduce the carbon emission of UCO biodiesel. Glycerol, as the co-product during trans-esterification process, contains 16 MJ/kg of energy. The yield of glycerol is ~0.10 Tones/ton biodiesel. Therefore, there would be approximately 160 MJ of energy available potentially from glycerol when 1 ton biodiesel is produced. If the energy in glycerol is recuperated, the carbon footprint of biodiesel could be reduced.

Conclusions

Direct use of the SUCO in diesel engines without trans-esterification can deliver more carbon reductions compared to its counterpart UCO biodiesel. The LCA results on WTW carbon footprint showed that the carbon footprint of the SUCO fuel is 1.76 gCO_2e/MJ, demonstrated a 98% reduction compared to fossil diesel (87 gCO_2e/MJ) and a 54% reduction compared to UCO biodiesel (3.80 gCO_2e/MJ). This makes the SUCO fuel a real carbon neutral fuel.

Compared to the conventional ways of utilization of the UCO which converts the UCO into biodiesel, the SUCO renewable fuel removed the transesterification stage and reduced carbon footprint by 54% compared to the UCO biodiesel. Even if the by-product (glycerol) was recovered, the merit of SUCO in carbon emission reductions compared UCO biodiesel is still significant.

The potential of the SUCO renewable fuel on carbon savings is significant. However, as the SUCO renewable fuel has higher viscosity, lower volatility compared conventional fuels, a modification of the engine fueling system is needed. In this research, an intelligent on-board fuel blending system has been employed. The initial vehicle trials showed that the SUCO renewable fuel can provide satisfactory operational performance. Thus the carbon reduction potential by the SUCO fuel is practical and achievable. The other disadvantage of SUCO is that extra fuel storage tanks for SUCO at fleet depots are needed.

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Definitions/Abbreviations

DfT: Department for Transport

HGV: Heavy goods Vehicle

LCA: Life Cycle Assessment/Analysis

PM: Particulate Matter

PTO: Power Take off

SUCO: Straight Used Cooking Oil

SVO: Straight Vegetable Oil

UCO: Used Cooking Oil

UHC: Unburnt Hydrocarbons

TTW: Tank To Wheel

UK DfT: UK Department for Transport

WTT: Well To Tank

WTW: Well To Wheel

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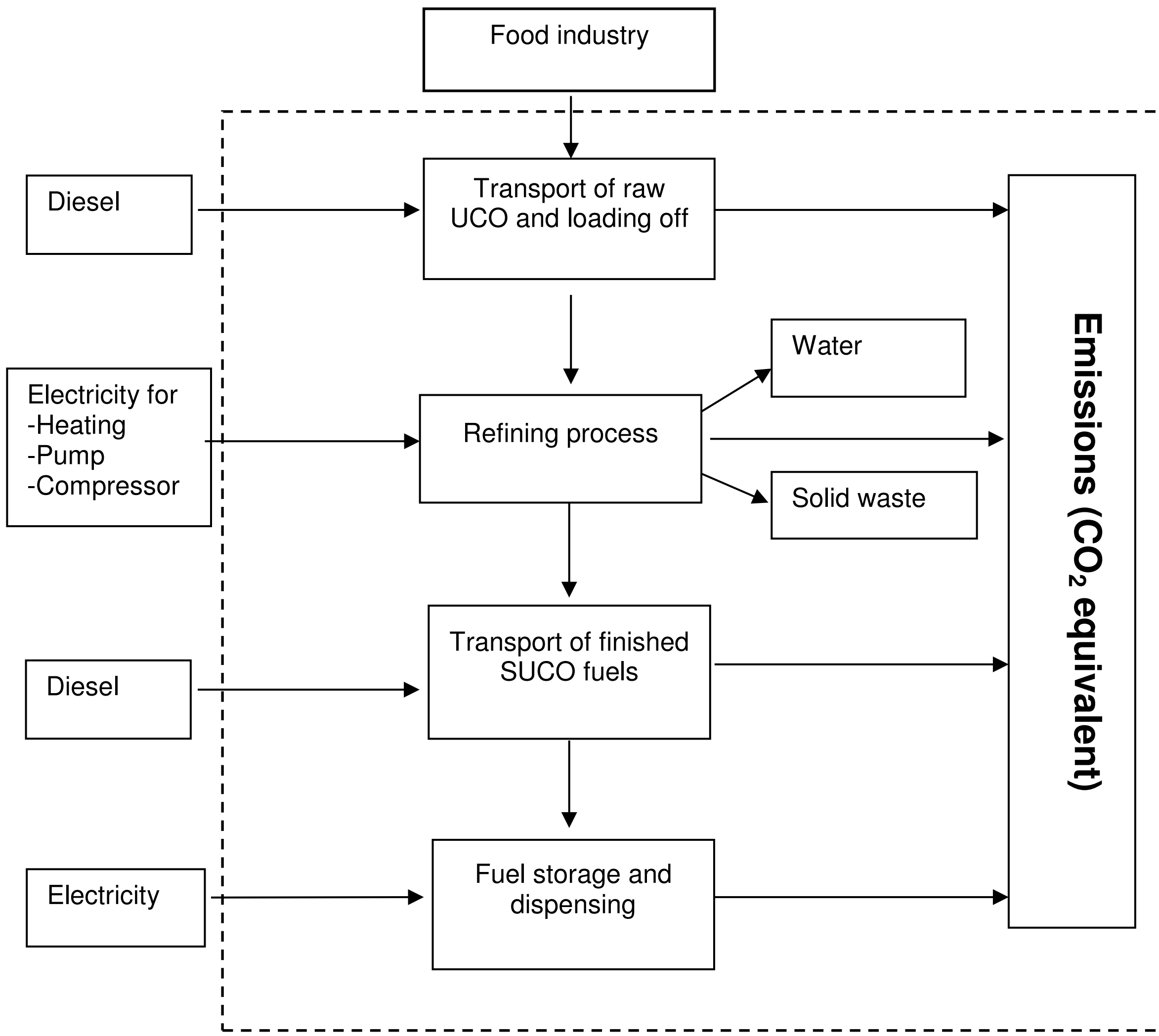
Appendix A:



Food industry
Diesel
Transport of raw UCO and loading off
Water
Electricity for
-Heating
-Pump
-Compressor
Refining process
Solid waste
Emissions (CO_2 equivalent)
Diesel
Transport of finished SUCO fuels
Electricity
Fuel storage and dispensing