

WASTE-TO-FUEL OPPORTUNITIES FOR BRITISH QUICK SERVICE RESTAURANTS: A CASE STUDY

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Abstract

The fast food supply chain is facing increasing operating costs due to volatile food and energy prices. Based on a case study of a major fast food logistics operator, this paper quantifies the potential for fuel generation from the waste generated by quick-service restaurants in Britain. Several fuel pathways and supply chains were mapped to understand the carbon intensity of the various waste-to-fuel opportunities, the number of heavy goods vehicles that might be powered and the key factors that could help companies make better informed decisions related to fuel generation from waste.

The research suggested that depending on the scenarios considered, between 13.9 and 17.2 million GJ of energy could be obtained from fuels made from the waste arisings of British quick service restaurants and their distribution centres (DCs), representing between 4.4 and 5.8% of the national energy consumption from heavy goods vehicles (HGVs) and Well-to-Wheel (WTW) Greenhouse Gases (GHG) savings of between 652-898 thousand tonnes of CO₂ equivalent annually.

Used cooking oil and burger fat arising from British quick-service restaurants could generate enough energy to power up to 3,891 HGVs with FAME diesel (B100), 1,622 with HVO diesel (B100) or 1,943 with biomethane annually. The paper and card generated by these same establishments could also power an additional 4,623 biomethane vehicles, wood pallets could power an additional 73 bioethanol trucks and plastics could also power 341 vehicles running with synthetic diesel.

The results showed that collections of separate waste fractions by logistics operators could make a relevant contribution towards the decarbonisation of the supply chain while reducing disposal fees and fuel costs. The carbon emissions resulting from this approach depend greatly on the footprint of the collection and transportation systems used to move waste from the restaurants to the processing plants and return the converted fuel back to the distribution centres where the vehicles are refuelled. Logistics firms are in a privileged position to manage these flows as they can use empty back-haul trips to collect and consolidate waste in distribution centres.

Keywords

Biomass; fuel; energy; GHG; restaurant; waste

1. Introduction

The economic recession has forced supply chain operators across the EU to reassess their operations in order to remain competitive. Customers are also becoming more sensitive toward issues of sustainability, and organisations must reconcile these concerns with their triple bottom line (people, planet and profit) as a way to improve stakeholders' loyalty (Elkington, 1998). Rising food prices coupled to volatile energy prices and concerns related to environmental sustainability and energy security have led to increased interest in how to maximise the use of existing resources, particularly the waste-to-fuel opportunities arising from the food supply chain. According to Hollins (2013), UK hospitality and food service outlets only recycle, send to anaerobic digestion (AD) or compost 46% of the 2.87 million tonnes of waste generated each year. Designing products for a circular economy could allow UK supply chains to become virtually waste free whilst generating an income stream of \$1.5 billion (equivalent to approx. £0.9 bn. as of 31/12/2013) per year or around \$172 (£104 as of 31/12/2013) profit per tonne of food waste (Ellen MacArthur Foundation, 2013). This paper uses a detailed investigation of a British fast food supply chain (FFSC) to understand the nature of the co-products and by-products produced, how these are currently treated, and the scope for their secondary utilisation in the operation of logistics fleets.

1.1 The British Fast Food Supply Chain

Quick service restaurants (QSRs) account for 12.1% of hospitality sector outlets in the United Kingdom (UK) (WRAP, 2011) and generate annual revenues in the region of £5.5bn (IBISWorld, 2013). They are responsible for generating 246,000 tonnes of waste annually with less than 57% of this being recycled, reused or composted (WRAP, 2011). Hollins (2013) estimated the total food waste of UK QSRs in 76,000 tonnes (including fast food, take-aways, fish and chip shops and sandwich bars), representing £277 million per year (at £3,500/tonne) from which just 17,000 tonnes were unavoidable. With retail diesel costs having increased by almost 40% from 2004 to 2014 (DECC, 2015), there is growing interest in whether waste arisings can be used as a supplementary fuel, given that biofuels have been shown to deliver substantial greenhouse gas (GHG) emissions savings, avoiding negative indirect land use changes and relieving pressures on food prices. The whole UK food chain emitted around 115 million tonnes of CO₂eq. in 2009¹ (Defra, 2011) with the commercial transportation of food for UK consumption representing around 9% of these GHGs emissions (Defra, 2011) and between 1.8% (FRPERC et al. , 2010, Smith et al. , 2005) and 2.5% (Garnett, 2003) of total UK carbon emissions.

1.2 Waste Streams

QSRs typically operate separate waste collections for paper and card, plastics, used cooking oil (UCO) and grease trap waste (GTW), kitchen food waste, glass and wood among other fractions. Waste arisings at QSRs also result from damage to products during handling, storage and transportation as well as from products discarded by customers. A survey conducted by WRAP (2011) reported that mixed waste from UK QSRs generally consisted of kitchen food waste (51%), paper (15.1%), card (8.6%), dense plastics (4.8%), plastic film (6%) and glass (3%). It was estimated that UK QSRs produced around 16,300 tonnes of paper and 9,200 tonnes of card as mixed waste in 2009 (WRAP, 2011). Thermoplastics are widely used in the FFSC as packaging, and UK QSRs produced around 5,200 tonnes of dense plastic and 6,300 tonnes of plastic film in 2009 (WRAP, 2011).

In 2009, the UK food chain produced 15 million tonnes of drink and food waste, almost half coming from households, 3.2 million from manufacturing and 0.6 million linked to the UK hotel and catering sectors (Defra, 2011). From the 54,700 tonnes of food waste produced by QSRs (0.3% of the total) 15,500 tonnes were avoidable (WRAP, 2011). To put this into perspective, Tesco generated 28,500 tonnes of food waste in the first two quarters of 2013, mainly from bakery products and fruit and vegetables (Houses of Parliament, 2013).

In Europe, an estimated 14.6% of meat and 19% of fish are wasted between distribution and point of consumption (Gustavsson et al. , 2011); Defra's estimate for the UK is considerably lower and suggested that 13% of edible meat and fish are wasted (Defra, 2013a). The UK produces around 14 billion litres of milk annually (C-Tech Innovation Ltd, 2004) and over 1 billion litres (7%) are estimated to be wasted along with 26.5% of cereals, 23% of potatoes and 27% of fruit and vegetables between distribution and consumption (Gustavsson, Cederberg, 2011).

In Europe, the main oil crops are sunflower and rape seed (C-Tech Innovation Ltd, 2004) which are the main ingredients in the vegetable cooking oils used by one of the leading UK fast food supply chains. British QSRs generate significant amounts of UCO with Kentucky Fried Chicken (KFC) collecting 7.75 m litres

¹ Excluding overseas production, food packaging, food waste and land use change.

53 annually (KFC, 2012) and McDonalds over 3.6 m litres (McDonald's, 2012), not including GTW from
54 wastewater interceptors or separately collected burger fat. More efficient cooking technologies such as air fryers
55 and healthier meal options may reduce the availability of UCO in the future, with Burger King and McCain
56 having already introduced fries with 40% less fat in 2013 (Burger King, 2013).

57 1.3 Waste-to-Fuel Opportunities for British QSRs

58 Biogas is typically obtained from AD or landfill gas recovery from organic waste feedstocks such as fish,
59 meat, fruit, vegetables, dairy products, wasted oil, fat, paper and cardboard. In August 2011, there were 66
60 plants in the UK treating around 1 million wet tonnes of food and agricultural waste (Houses of Parliament,
61 2011); this increased to 78 plants by June 2012 (NNFCC, 2012). To convert this biofuel into biomethane
62 compatible with CNG (compressed natural gas) trucks, the biogas needs to be upgraded to 95% methane,
63 venting or capturing the CO₂ by-product. Biomethane as a fuel for transportation is gaining popularity, with
64 three of the 23 LNG (liquid natural gas) and three of the 8 CNG dedicated refuelling facilities currently
65 registered in the UK using biogenic content (Gas Vehicle Hub, 2014). Alternatively, energy producers can use
66 biomethane in combined heat and power plants (CHP) to reduce their energy costs and GHG emissions. When
67 the fuel is generated through AD, the residue of the process (digestate) can also be used as a biological fertilizer
68 reducing the need for synthetic fertilizers (Banks et al. , 2011, Heaven et al. , 2011). If the digestate complies
69 with the requirements of the Publicly Available Specification BSI (PAS) 110, it is no longer considered a waste
70 and does not attract disposal costs.

71 The paper industry generates pulpwood waste, black liquor and coke from the paper Kraft process and there
72 is potential for producing methane from these wastes (Lin et al. , 2011, Magnusson and Alvfors, 2012, Rintala
73 and Puhakka, 1994) with some large paper manufacturing companies installing CHP plants to use the biogas
74 obtained from their recycling processes (Saica Natur, 2012). Besides AD, energy efficient recovery pathways
75 for paper, cardboard and wood waste (pallets) include combustion and incineration with heat recovery and at a
76 smaller scale, gasification and pyrolysis of ligno-cellulosic waste. Gasification is more appropriate in
77 applications where there is a use for heat while pyrolysis is typically used to transform biomass into liquid fuels
78 (Panwar et al. , 2012). The char produced during pyrolysis can also be gasified to produce syngas which is
79 energy-rich in hydrogen, methane, monoxide of carbon and other compounds. GHG savings of 98% have been
80 reported by using black liquor from waste wood as feedstock from the paper industry (Edwards et al. , 2014).
81 The Conservation of Clean Air and Water in Europe (CONCAWE) report estimates that synthetic diesel can
82 yield GHG savings of 97% by using the Fischer-Tropsch approach (Edwards, Larive, 2014). This gas-to-liquids
83 chemical process converts a mix of gases (monoxide of carbon and hydrogen) into liquid hydrocarbons
84 (Damartzis and Zabaniotou, 2011). Currently, the only Biomass-to-Liquid (BTL) initiative in the UK is a pilot
85 plant producing biobutanol (Bioenergy2020+, 2013), a fuel that can be blended with petrol. As the majority of
86 the HGV fleet in the UK runs on diesel, there is very little scope for making any impact on this specific market
87 in the short term.

88 UCO from the food industry is widely recycled in the UK and constitutes one third of all Fatty Acid
89 Methyl-Ester (FAME) biodiesel feedstock (DfT, 2013a). In the UK, there are 30 registered medium and large
90 UCO collectors and biodiesel producers (organisations with more than 50 employees) with the capacity to
91 process 250 million litres of UCO per year (Environmental Audit Committee, 2012). First generation biodiesel
92 converts UCO into FAME biodiesel through transesterification; however, current commercial second generation
93 biodiesels convert UCO into hydrogenated vegetable oils biodiesel (HVO), obtaining bio propane as a co-
94 product (DECC, 2014a). Sunde et al. (2011) found that HVO made from UCO outperforms FAME biodiesel
95 and BTL biodiesel from woody material, with respect to environmental life cycle impact and costs. FAME
96 biodiesel from UCO can deliver 84% GHG savings (WOFA3 pathway) compared to 91% for HVO biodiesel
97 (Edwards, Larive, 2014). Unfortunately, there are currently no second generation commercial biodiesel
98 production plants in the UK. A summary of the GHG savings that could be realised from using different biofuels
99 made from QSR waste feedstocks is shown in Table 1.

100 Most plastics and films come from fossil oils and can be recycled a number of times into new plastics
101 avoiding the production of new virgin plastic. They can also be converted into hydrocarbon fuels (Kaminsky et
102 al. , 2004, Michaud et al. , 2010) with each tonne of mixed plastic yielding between 700 litres (SITA UK, 2011)
103 and 1,201 litres of consumer ready diesel (4R Sustainability Inc., 2011) depending on whether other oil
104 distillates are also obtained in the process. In the UK, SITA plans to open 10 processing plants with the capacity
105 to recover energy from 60,000 tonnes of mixed plastic waste per year, resulting in a diesel with a higher cetane
106 number and at a lower cost (SITA UK, 2011). The GHG emission factor for recycled plastic is 0.6 kg CO₂eq./kg
107 versus 2.5-4.5 kg CO₂eq./kg for new plastic (Hill et al. , 2013). For this reason, it is not widely considered
108 optimal to produce synthetic fuel from plastics that have not reached their end of life as this would reduce the
109 availability of recycled plastic, forcing companies to buy products made from virgin material. Another

110 alternative to reduce emissions from plastic consumption is increasing the proportion of bioplastics in
 111 packaging; however, this is not always technically feasible. Bioplastics can protect firms against rising prices of
 112 mineral oil derived plastics as some of them can also be digested to produce biogas, a preferred option over
 113 composting in respect to energy demand and depletion of natural resources (Michaud, Farrant, 2010).

114 Table 1 GHG balances for different fuel and biofuel pathways. Adapted from: Edwards, Larive (2014)

Pathway Code	Feedstock	Fuel	Total WTT GHG (g CO ₂ eq./MJ final fuel)	Total TTW GHG (g CO ₂ eq./MJ final fuel)	Total WTW GHG (incl. combustion) (g CO ₂ eq./MJ final fuel)	GHG Savings (%) vs. Baseline
COD1	Mineral Oil	Diesel	13.8	74.8	88.6	Baseline Diesel Pathway
COG1	Mineral Oil	Gasoline	12.2	74.9	87.1	Baseline Gasoline Pathway
GMCG1	Mineral Gas	CNG (EU-Mix)	11.8	57.5	69.3	Baseline Gas Pathway
OWCG1	Municipal Waste	Compressed Biogas	11.3	3.5	14.8	83% vs. COD1 79% vs. GMCG1
WWET1	Waste Wood	Ethanol (Gasoline)	19.3	0.2	19.5	77.6% vs. COG1
WOFA3a	Waste Cooking Oil (UCO)	FAME Diesel	13.6	0.2	13.8	84% vs. COD1
WOHY1a	Waste Cooking Oil (UCO)	HVO Diesel	13.0	-4.9	8.1	91% vs. COD1
TOFA3a	Tallow	FAME Diesel	26.2	0.1	26.30	70 % vs. COD1
TOHY1a	Tallow	HVO Diesel	29.7	-5.2	24.50	72% vs. COD1

115

116 2. Methodology

117 The study was based on a substantial database of waste collection movements from a major global fast food
 118 chain, comprising 34 months of separated waste collections from January 2012 to October 2014 from more than
 119 1,000 British QSRs and their associated DCs.

120 The most realistic waste-to-fuel pathways based on the case study were estimated using the current EU
 121 waste-to-fuel production infrastructure and the most feasible HGV powertrain technologies. The potential yields
 122 (Table 2) along with the analysis of the waste collection data, were used to produce an annual waste profile for
 123 each restaurant. This waste profile was then extrapolated to the total number of British QSRs (39,762) providing
 124 an estimate of the waste-to-fuel potential across the sector.

125 2.1 Categories of Waste

126 An analysis of the case study organisation showed the main waste types at different stages of its supply chain
 127 (Figure 1). The segregated waste fractions considered in this study included waste streams produced by the
 128 restaurants such as UCO, burger fat, cardboard, plastic films and bottles, and food waste from the kitchens. Data
 129 were also collected on the separate collections of food waste, wooden pallets, plastic film, cardboard and paper
 130 from the DCs. The WRAP report (WRAP, 2011) estimated that British QSRs produce around 246,000 tonnes of
 131 waste per year. According to our analysis, this figure is a serious underestimate as just separate collections of
 132 cardboard already represent more than double this amount. The main reasons for this, as suggested in their

133 methodology, was their lack of access to data from large corporations and the small sample size. This study, on
 134 the other hand, has managed to access data representing over a thousand QSRs with accurate data of the total
 135 tonnage of waste fractions collected separately sent to recycling; however the fractions with no real potential for
 136 producing transportation fuels, were not included in the analysis.

137 Table 2 Energy yields from different feedstocks and pathways. Assuming that ρ of methane is 726.3 kg/m³ and
 138 conventional diesel ρ =839.6 kg/m³.

Pathway Code	Waste Feedstock	Fuel	Conversion Factors	Conversion (weight / weight) %	Literary Source
WOFA3a	UCO	FAME	0.96 tonnes (output)/tonnes (input) refining	90.91%	E4Tech and Concepto (2013) *
			0.947 tonnes (output)/tonnes (input) transesterification		
WOHY1a		HVO	0.405 tonnes (output)/tonnes (input) refining	32.04%	E4Tech and Concepto (2013) *
			0.791 tonnes (output)/tonnes (input) hydrogenation		
WOCG1	Used Vegetable Oil	Bio-Methane	0.6485 m ³ /kg VS added	47.10%	Labatut et al. (2011) *
	Waste Edible Oil		1.104 m ³ /kg VS added	80.18%	Braun et al. (2003)
TOFA3	Burger fat (Tallow)	FAME	0.96 tonnes (output)/tonnes (input) refining	90.91%	E4Tech and Concepto (2013) *
			0.947 tonnes (output)/tonnes (input) transesterification		
TOHY1a		HVO	0.405 tonnes (output)/tonnes (input) refining	32.04%	E4Tech and Concepto (2013) *
			0.791 tonnes (output)/tonnes (input) hydrogenation		
TACG1	Animal fat (Tallow)	Bio-Methane	1.0 m ³ /kg VS added	72.63%	Braun et al. (2003)*
FFCG1	Fast Food Waste	Bio-Methane	0.693 m ³ /kg VS added	50.33%	Braun et al. (2003)
			0.473 m ³ /kg VS added (pasteurised sample)	34.35%	Banks and Zhang (2010)*
CACG1	Cardboard	Bio-Methane	0.267 m ³ /kg VS added (pasteurised sample)	19.39%	Banks and Zhang (2010)*
PACG1	Office Paper	Bio-Methane	0.137 m ³ /kg VS added	9.95%	Banks and Zhang (2010)*
WWET1	Wooden Pallets	Bio-ethanol	0.98 tonnes (output)/tonnes (input) wood crushing	16.27%	E4Tech and Concepto (2013) *
			0.166 tonnes (output)/tonnes (input) production		
PFSB	Plastic Film (LDPE)	Synthetic Diesel EN590	Between 750L/tonne (Cynar Plc) and 950L/tonne (Klean Industries)	Average 73.32%	Adapted from: 4R Sustainability Inc. (2011) *
PBSD	Plastic Bottles (HDPE)				

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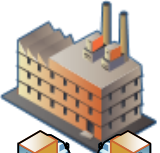


TYPE WASTE	PRODUCTION		PROCESSING	DISTRIBUTION	QUICK SERVICE RESTAURANTS
	Meat, Fish & Dairy 	Agriculture & Other Raw Materials 			
Organic Losses & Waste	Dead Animals Manure Paper & Cardboard Pallets	Mechanically Damaged parts & Seed Losses Hard parts of Plants	Non-commercial Parts By-products: Tallow, Oil cake, Fish Meal Paper & Cardboard Wooden Pallets	Out of Date Food & Expired Promotions Paper & Cardboard Wooden Pallets	Used Cooking Oil, Fat, Coffee Grounds & Food Leftovers Paper & Cardboard Packaging & Cups
Other Organic Waste (Effluents)	Sludges	Cleaning Water (Vegetables)	Blanching, CIP Cleaning & Water Effluent	Cleaning Water Interceptors	Drinks, Ice Creams & Cleaning Water
Non Organic Losses & Waste	Plastic & Film Packaging	Plastic & Film Packaging	Plastic & Film Packaging	Plastic & Film Packaging	Plastic & Film Packaging, Plastic Cutlery & Bottles

Figure 1 Main waste streams in the fast food supply chain with waste-to-fuel potential.

The wastes that the FFSC can convert into usable fuels for transportation were classified into three main categories: organic waste, non-organic waste and water effluent. Organic waste includes animal losses and manure, damaged vegetables, by-products of processing and rendering such as tallow, oil seed cake, bone meal as well as out of date food from DCs and food wastage from restaurants. UCO and fat from cooked burgers and lingo-cellulosic wastes are also included in this category. The latter comprises non-edible parts of plants, card and paper used in packaging and food containers, and wooden pallets used in transportation. Non-organic waste comprises mainly packaging film, plastic cases for transportation of goods and plastic bottles for drinks. A category for waste effluent was also included as this typically goes into the foul drain and ends in water treatment plants where organic effluents are treated producing biogas as a by-product.

Due to the limitations of this study, the boundaries were setup between distribution and QSRs. Waste streams from production and processing were excluded and the authors acknowledge some limitations in the methodological approach as a result. The quantitative analysis of over 1000 QSRs (around 2.5% of the British market) may not represent the waste profile of QSRs specialised in other types of foods. Future research could benefit from surveying and characterising other franchises and QSR waste to reveal a more precise waste profile. This study excludes fish and chip shops because they are not classified as 'fast food restaurants and takeaways' by the Ordnance Survey geographical information dataset used in this research and access to segregated data for waste collections from such shops were not available.

2.2 Data Analysis

Accurate monthly waste tonnage data from QSRs and DCs were supplied by a third party logistics provider (3PL) managing the supply chain for the case study organisation from January 2012 to October 2014, with additional data provided by a third party waste management organisation. The total tonnage was divided by the number of restaurants to provide a mean waste profile per restaurant and year. This profile was extrapolated to the total number of fast food outlets in Great Britain, considered to be 39,762 according to data supplied by Ordnance Survey (2014) for the class count 01020018 (fast food and takeaway outlets).

Unstructured interviews with the directors of two 3PL companies working in the fast food sector provided an insight into the challenges of waste management from an operational and legal perspective. Additional interviews were also conducted with several European truck manufacturers to ascertain the technology roadmaps of different fuel technologies and the impact of Euro 6 emissions standards on UK HGV fleets. Interviews with logistics operators and vehicle manufacturers, combined with a literature survey, allowed a range of realistic and feasible pathways for the conversion of QSR wastes into transportation fuels to be identified.

176 2.2.1 *Energy Yields*

177 Data on the energy yields from waste feedstocks for each pathway were obtained from multiple sources (Table
178 2). In this study, UCO was considered to be the same as used vegetable oil and waste edible oil; and burger fat,
179 similar to tallow or animal fat. GTW was not included in this study as there were no detailed data related to
180 interceptor's collections tonnage. The calculations made took into consideration the conversion factors
181 appearing with an asterisk (*) in Table 2. FAME represents feedstocks that have been converted into biodiesel
182 through the transesterification process; also known as first generation biofuel, with HVO biodiesel being
183 obtained through hydrogenation known as second generation biodiesel. Bio methane is typically obtained
184 through AD. The biomethane production potential from feedstock was calculated either as a main substrate or as
185 a co-substrate (Table 2). Woodchips can be converted into biomethanol or bioDME (dimethyl ether) through
186 gasification; however it is also possible to produce bioethanol, biogasoline and biodiesel through enzyme
187 hydrolysis fermentation yielding more advanced second generation biofuels but at a higher expense than
188 conventional fuels. Examples of commercial stage plants in Europe for these pathways are only found in Nordic
189 countries (BioDME, 2012, Sekab, 2013). Pyrolysis is also the main process to produce synthetic diesel from
190 plastics. The conversion efficiency factor used in this study for plastic-to-fuel corresponds to the average of the
191 values reported by a number of companies working in the sector as reflected in the 4R Sustainability Inc. (2011)
192 survey.

193 To convert litres of UCO and tallow into kg, the yearly production was converted to kg assuming that both
194 have a density of 0.92 kg/ L and a density for FAME biodiesel of 0.89 kg/ L and 0.78 kg/L for HVO biodiesel.
195 Also, based on the values reported by Edwards, Larive (2014), the densities of bioethanol and synthetic diesel
196 considered were 0.794 kg/L and 0.78 kg/L respectively.

197 2.2.2 *Well-to-Wheel Carbon Accounting of Waste-to-Fuels*

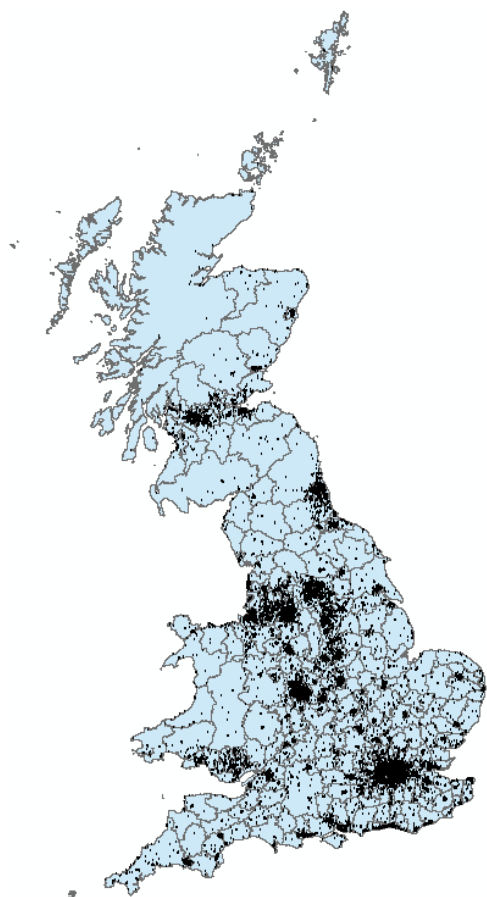
198 The GHG emissions of growing or producing waste feedstocks are attributed to the QSR chains that procured
199 them. The Well-to-Wheel (WTW) GHG emissions included are the sum of Well-to-Tank and Tank-to-Wheel
200 emissions. Tank-to-Wheel (TTW) emissions are those emitted while consuming (burning) the fuels. The TTW
201 emission factors and densities used in this study for each final fuel are the ones reported by Edwards, Larive
202 (2014) in the CONCAWE report (Table 1). In this case, Well-to-tank (WTT) emissions are those emitted as a
203 result of all the processes that make possible the conversion of waste into fuel. These include the collection,
204 transportation, storage, manipulation, handling, and conversion of feedstock (waste) into fuel, and its subsequent
205 transportation, storage, manipulation, handling and dispensing. The WTT carbon intensities and energy yields
206 were calculated with the assistance of the UK Carbon Calculator (E4Tech and Concepto, 2013) using the energy
207 yields marked with an asterisk (*) in Table 2. Transportation emissions represent a significant contribution to
208 overall WTT GHG emissions. When moving liquid or solid feedstocks, appropriate liquid/bulk freight vehicles
209 and vessels were assumed and their TTW emissions were the default options in the UK Carbon Calculator
210 (E4Tech and Concepto, 2013), unless specified otherwise.

211 GHG reporting depends on carbon accounting practices, the emissions factors of each energy pathway and
212 year, and the total fuel consumed. When information regarding the latter is not available, the UK carbon
213 reporting methodology followed by DECC (2014b) makes assumptions regarding driving cycles and loading
214 factors. In this study, as the exact quantity of fuel consumed by the QSR fleet was known, it was possible to
215 calculate the WTW GHG emissions directly without need to evaluate driving cycles, vehicle types or loading
216 factors. It was assumed that during back-haul trips, each delivery truck was empty and the carbon emissions of
217 waste collections made by the 3PL fleet were almost negligible, contributing just marginally to the fuel
218 consumption due to the increase in vehicle mass compared to an otherwise empty back-haul trip.

219 2.2.3 *Geographical Data and Geographic Information Systems*

220 The UK Carbon Calculator allows the parameterisation of distances and modes of transport as well as energy
221 requirements associated with intermediate waste-to-energy processes (e.g. transportation, handling, processing,
222 storage and refuelling) and emission factors of the national energy grid. The distances between QSRs and DCs
223 were taken as the averages observed for the case study supply chain as shown by the routing and scheduling
224 software and using shortest-path algorithms for the whole year. As a typical trip was around 280 km, this means
225 that the return trip is half of this and as around 4 deliveries are undertaken, it was considered that 35 km can be
226 attributed to each restaurant. Distances between the DCs and fuel processing plants were calculated using
227 Google Maps (2013) for all road haulage trips. When waste was shipped abroad for processing, the port of
228 origin was taken to be Felixstowe, the port of destination was the one closest to the location of the waste
229 processing plant and the distances were obtained using Searates.com (2013). The location of British QSRs were
230 obtained from Ordnance Survey (2014), Figure 2. The transport related energy consumed by HGVs for each

231 British district was obtained from the sub-national road transport fuel consumption dataset produced by DECC
232 (2013). Both datasets were combined to create a map with ArcGIS illustrating the percentage fuel equivalent
233 consumed by HGVs that could be replaced by fuels produced from the waste streams from QSRs according to
234 different operating scenarios.



235
236 Figure 2 The distribution of the 39,762 fast food and takeaways restaurants in the Great Britain (2013).

237 3. Results

238 3.1 Feasible Waste-to-fuel Pathways for British FFSCs

239 The main waste-to-fuel pathways for this supply chain and the HGV engine technologies that can be powered by
240 these are shown in Table 3. There are two main types of powertrains: internal combustion engines (ICE) and
241 electric motors. ICE diesel engines are the standard among UK HGV fleets (DECC, 2013) but there is a growing
242 interest among logistics operators in ICE CNG trucks, vehicles that are also compatible with biomethane, as
243 they can lead to substantial cost and GHG savings. Other ICE engine technologies such as BioDME or
244 Biomethanol also appear in Table 3; however, such HGVs are currently only being tested in small-scale trials by
245 Volvo (BioDME, 2012). HGVs powered by electric motors can use the fuels identified in this study to derive
246 energy by using fuel cells directly or by obtaining electricity from CHP or waste-fired power plants. Solid oxide
247 fuel cells (SOFC) produce energy from the reformation of hydrocarbon fuels (e.g. diesel/biodiesel, biomethane);
248 however these powertrains are still only at a research stage and are currently being developed for auxiliary
249 power units (DESTA Consortium, 2014, TOPSOE, 2010). Proton exchange fuel cell (PEMFC) powertrains use
250 the hydrogen obtained from the gasification of biomass to transform energy into electricity with some examples
251 of such HGV technology being found in the port drayage sector (Vision Industries Corporation, 2012).

252 Some engine technologies can also reduce GHG emissions through the combination of fuels or
253 hybridisation of powertrains. Typically, dual fuel vehicles use a mix of diesel and methane (or
254 biodiesel/biomethane) and bi-fuel trucks can use either of them but not both simultaneously. Hybrid series or
255 parallel powertrain HGVs typically combine an internal combustion engine with an electric motor powered by a
256 battery pack and are best suited for urban logistics, where frequent stop-start operations maximise fuel savings.
257 Currently, the hybrid HGVs found during this research can reach up to 40 tonnes gross vehicle weight such as
258 the e-Highway HGVs developed by Siemens (2014). Alternatively, any of the fuels obtained from waste can be
259 converted into renewable power in CHP plants, allowing the use of electric plug-in HGVs with very low carbon

260 emissions. Any of the waste feedstocks originating in the FFSC can yield a broad range of fuels depending on
 261 the pathway followed (Table 3), as well as other potentially valuable by-products. The production of FAME
 262 biodiesel and of biomethane are the simplest pathways to produce renewable fuels in the UK due to the
 263 existence of a well-developed market for UCO and tallow collections, and the large number of AD plants. In
 264 addition, vehicles using either of these fuels meet most of the requirements of hauliers regarding power and
 265 range (Cope, 2011). Second generation biodiesel pathways were also studied; however, all commercial plants
 266 were located outside the UK and this increased GHG emissions of such pathways.

267 Table 3 Main waste-to-fuel pathways in the fast food supply chain and current HGV powertrain technologies
 268 that can benefit from these.

Industry	Sectors	Waste Type	Energy Recuperation Processes	Fuel Produced	Powertrain Technology
Food & Drinks	Agricultural Production, Storage & Processing	Product Losses & Waste	Anaerobic Digestion	Biomethane	ICE (Natural Gas)
		Non-edible parts	Biomass-to-Liquid	Biodiesel 2 nd generation	ICE (Diesel)
		Oil seeds Losses	Transesterification	Biodiesel 1 st generation	
			Hydrogenation Vegetable Oil	Biodiesel 2 nd generation	
			Water effluent	Anaerobic Digestion	Biomethane
	Animal Production & Meat Processing	Product Losses & Waste	Anaerobic Digestion	Biomethane	ICE (Diesel)
		Fat	Trans esterification	Biodiesel 1 st gen.	
			Hydrogenation Vegetable Oil	Biodiesel 2 nd generation	
		Slurry, Manure	Anaerobic Digestion	Biomethane	ICE (Natural Gas)
	Dairy	Milk			
		Water Effluent			
	Drinks	Water Effluent			
		Fruit Pulp			
	Quick Service Restaurants	Food waste & leftovers	Trans esterification	Biodiesel 1 st generation	ICE (Diesel)
		Coffee Grounds			
		Used Cooking oil & Grease Tap Waste	Hydrogenation Vegetable Oil	Biodiesel 2 nd generation	
		Mixed Waste: Paper & Card	Anaerobic Digestion	Biomethane	ICE (Natural Gas)
Mixed Waste: Plastic & Film		Pyrolysis	Synthetic Diesel, Methane, DME, Methanol, Hydrogen	ICE. (Diesel, DME, Methanol, Hydrogen), Electric (SOFC)	
Thermoplastics & Film					
Oil & Plastics	Plastic Packaging	Bioplastics	Anaerobic Digestion	Biomethane	ICE (Natural Gas)
		Paper & Card packaging,	Black liquor	Anaerobic Digestion	Biomethane
	Pulp waste				

	Wood Pallets		Pyrolysis & Gasification (Syngas)	Synthetic diesel	ICE Diesel
				Bio Dimethyl Ether (BioDME)	Adapted Diesel, Adapted Petrol (70%LPG/30%DME)
				Hydrogen	ICE (Hydrogen)
					Electric (PEMFC)
				Bio Methanol	Electric (Direct Alcohol Fuel Cell) Adapted Diesel (5% additives)
				Bio Ethanol	ICE (Adapted Gasoline) ICE (Diesel with additives)
Biodiesel 2 nd generation	ICE (Diesel)				
Water	Water Treatment	Sewage, sludge	Anaerobic Digestion	Biomethane	ICE (Natural Gas)

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3.1.1 WTT Emissions for Different Feedstocks and Pathways from QSRs

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The carbon intensity and GHG savings of different waste-to-fuel pathways are shown in Table 4. Pathways WOFA3a and TOFA3a are the only ones currently followed by the case study QSRs. All the other pathways represent potential alternatives to produce fuels from waste considering specific feedstocks and conversion processes. The TTW values (Table 1) were added to the WTT values calculated to give the total WTW carbon intensity for each pathway (Table 4). The WTW GHG savings of the diesel and biodiesel pathways were then compared to the carbon intensity of the COD1, biomethane-to-GMCG1 and bioethanol-to-COG1 pathways as shown in Table 1. Compared to standard mineral diesel fuel, FAME biodiesel can save almost 85% WTW GHG emissions, a percentage that increases very slightly in the case of second generation biodiesel. Biomethane can yield almost 62% WTW GHG savings compared to fossil natural gas fuel and 70% compared to mineral diesel. Bioethanol saves almost 59% compared to gasoline and 59.4% when compared to diesel.

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Table 4 Average carbon intensity and GHG emission savings of different pathways for the food chain studied.

Pathway Code	Waste Feedstock	Fuel	Chain Carbon Intensity				WTW GHG Savings vs Fossil fuel pathway
			WTT Fuel	WTT	TTW	WTW	
			(kg CO ₂ eq./t biofuel)	(g CO ₂ eq./MJ)			
WOFA3a	UCO	FAME	499	13.4	0.2	13.6	84.7% vs COD1
TOFA3a	Burger Fat	Biodiesel	493	13.3	0.1	13.4	84.9% vs COD1
WOHY1a	UCO	HVO	666	15.1	-4.9	10.2	88.5% vs COD1
TOHY1a	Burger Fat	Biodiesel	654	14.9	-5.2	9.7	85.1% vs COD1
FFCG1	Food Waste	Biomethane	1,030	22.9	3.5	26.4	61.9% vs CMCG1
WWET1	Wood Waste	Bioethanol	714	35.8	0.2	36	58.7% vs COG1

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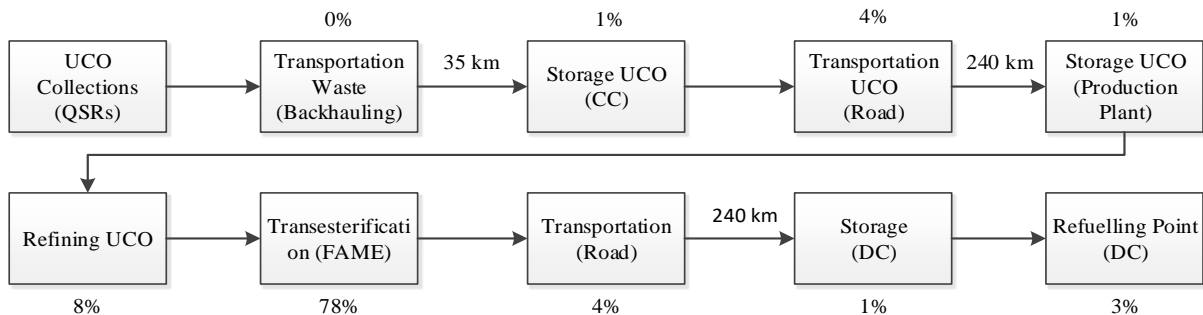
As can be seen in Table 4, WTT GHG emissions from first generation biodiesel are lower than those from second generation but despite their greater efficiency in converting waste to fuel, there are no commercial second generation biofuel production plants in the UK so the feedstock has to be shipped overseas, and the end fuel brought back to Great Britain. These long distances increase the carbon intensity of the TTW chain. If all feedstocks were processed in the domestic market or otherwise sold in the countries where those facilities are located, the WTW GHG savings would increase considerably. Benefiting from these additional carbon savings could be possible by developing an offsetting mechanism similar to Green Certificates applicable to transportation at an EU level. In this way, a feedstock could be processed in one country, shipped to another and bought into the local market without the need for physically importing it.

292 When considering the WTW emissions, with the exception of the WWET1 pathway, all others deliver the
 293 sustainability criteria as defined by the EU Directive 2009/28/EC which states that a biofuel must save at least
 294 60% GHG emissions to benefit from European subsidies (DfT, 2013b, European Commission, 2013). The
 295 results in Table 4 differ from those reported in Table 1, as they are specific to the supply chains studied. In
 296 Figures 3-6, the haulage distances are expressed in km while the percentages represent the contribution of each
 297 stage to the total TTW carbon intensity. The percentages shown represent the contribution of a particular stage
 298 to the overall GHG emissions for the waste-to-fuel pathway. Road and nautical distances have been converted
 299 into kilometres and quoted on top of the arrows representing the distance between origin and destination. The
 300 pathways from plastics to synthetic diesel have been excluded as no GHG emissions savings are expected.

301 3.1.1.1 WTT Emissions of UCO and Burger Fat to Biodiesel

302 Across all the case study restaurants, UCO and fat is collected in the QSRs, consolidated in a DC and converted
 303 into FAME biodiesel following the chain illustrated in Figure 3. As a potential alternative (not currently being
 304 undertaken) pathways WOXY1a and TOHY1a represent the same possibility for producing second generation
 305 biodiesel (HVO) from the same feedstocks (Figure 4).

306 In WOFA3a and WOXY1a pathways the oil is collected in an oil tank built into the HGVs. In TOFA3a and
 307 TOHY1a pathways, tallow is collected and transported in barrels from QSRs to the conversion plant. This
 308 reduces the carbon intensity as there is no energy consumption for transferring from/to and maintaining
 309 feedstock in storage tanks. Figure 3 shows the chain of UCO waste to FAME biodiesel production. Initially, the
 310 UCO is collected in small storage tanks located in the QSRs and pumped into larger 300 L oil tanks fitted in the
 311 delivery trailer's chassis. Once these arrive at the DC, the UCO is stored in a tank with a capacity of several
 312 thousand litres, awaiting collection from a third party processing organisation located at an average distance of
 313 240 km. The UCO is stored at the processing plant until it is refined and transesterified. The conversion process
 314 stages represent 86% of the total carbon emissions of the chain. The first generation biofuel is sent back to the
 315 DC where it is stored and made ready to be used by the logistics fleets. In this case the WTT carbon intensity
 316 calculated (13.4 g CO₂eq./MJ) is very similar to the one reported by Edwards, Larive (2014) in Table 1.



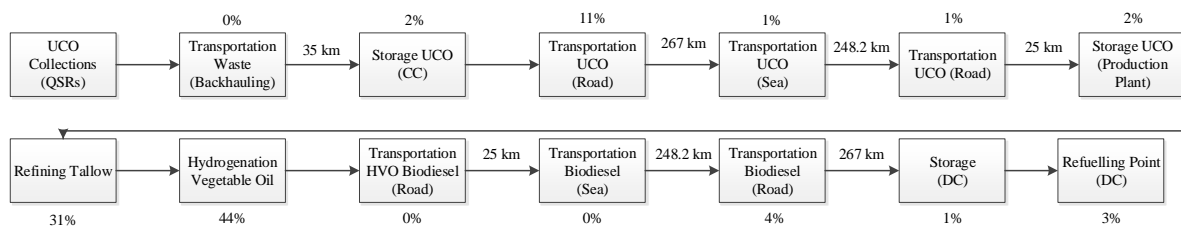
317 Figure 3. UCO to FAME biodiesel chain (WOFA3a pathway).
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319 TOFA3a pathway represents the conversion of tallow (burger fat) to FAME biodiesel. The stages are the
 320 same as the WOFA3a pathway with the only difference that fat is stored in barrels until it reaches the processing
 321 plant. There is thus no additional energy demand associated with its initial storage. This reduces the carbon
 322 intensity by 0.1 g to 13.3 g CO₂eq./MJ, around half of the value reported in Table 1. Refining and
 323 transesterification represent 87% of the total carbon emissions of this chain.

324 While first generation biofuels are produced in the UK, second generation biodiesel (e.g. HVO) is produced
 325 in the Netherlands, hence shipping waste overseas and bringing back the processed biofuel explains the increase
 326 in carbon emissions for the WOXY1a and TOHY1a pathways. The conversion of UCO and tallow into second
 327 generation biofuel is feasible; however, the production plant company contacted for this study indicated that a
 328 chemical analysis should be undertaken before accepting these types of feedstocks. Figure 4 illustrates the chain
 329 for conversion of UCO into HVO biodiesel (WOXY1a). The WTT carbon intensity for this pathway is 15.1 g
 330 CO₂eq./MJ, a value very similar to the one reported in Table 1. In this chain, waste is consolidated in the DC
 331 and transported an average distance of 267 km by road to the port of Felixtowe where it is shipped to Rotterdam
 332 (134 nautical miles) by a ship tanker. Once in the Netherlands, after a short trip by road, it reaches the Neste Oil
 333 processing plant. After the hydrogenation process, a high quality biodiesel is produced and it is assumed that
 334 this is shipped back to the DC in the UK where it can be stored and supplied to the fleet.

335 The TOHY1a pathway (fat to HVO biodiesel) chain is similar to Figure 4; however, tallow is transported
 336 in barrels all the way through. This means that the lorry carries dry product and that the ship is an ocean bulk
 337 carrier. On the way back, the liquid fuel is transported by sea tankers and trucks for liquids. This makes that the

338 initial storage, transportation by road and sea and hydrogenation percentages change to 0%, 10%, 2% and 45%
 339 respectively.



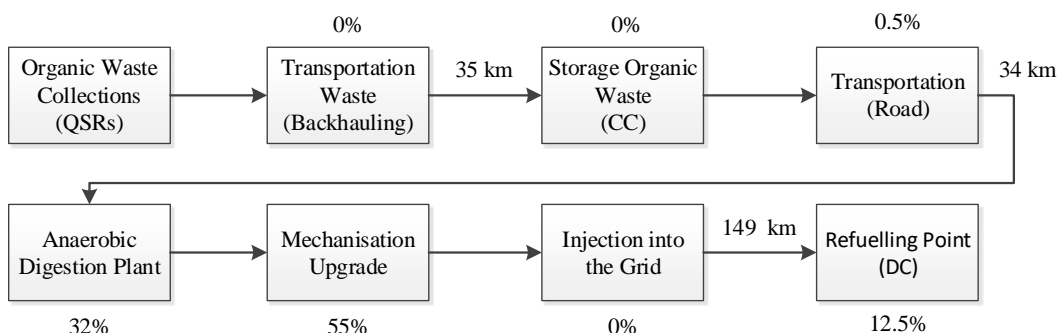
340
 341 Figure 4 UCO TO HVO biodiesel chain (WOHY1a pathway).

342 3.1.1.2 WTT Emissions of Food Waste to Biomethane

343 The FFCG1 pathway is represented in Figure 5. Food waste is collected in QSRs and stored in the DC where it
 344 is shipped to the closest AD plant. After the digestion of the waste, the biogas is upgraded to 95% biomethane
 345 and is injected into the UK natural gas grid. The biomethane can be consumed in the DC by natural gas HGVs
 346 engines as CNG. Refuelling represents a substantial percentage of the energy intensity of the chain (13%) as the
 347 gas has to be pressurised from 85 bar (national grid) to 250 bars (vehicle gas tank pressure). This is necessary as
 348 a higher pressure means lower fuel tank volume (at the same temperature) which minimises the impact on
 349 vehicle volumetric payload. Using LNG instead of CNG would increase vehicle range (for the same gas tank
 350 volume); however, this would add an additional step where the gas would have to be pressurised and kept at
 351 cryogenic temperature, increasing the carbon intensity of the chain even further and therefore reducing the GHG
 352 savings.

353 Consolidating food waste in the DCs and shipping such waste to the nearest AD plant generates 26.4 g
 354 CO₂eq./MJ of output energy (as shown in Table 4). This represents 70.2% lower carbon emissions than those
 355 reported in Table 1 for mineral diesel (88.6 g CO₂eq./MJ) and almost 62% lower than those for fossil natural
 356 gas. This result is slightly lower than the savings of 83% reported in Table 1 for the OWCG1 pathway; there,
 357 however, the organic fraction included all municipal wastes whilst in the FFCG1 pathway only fast food waste
 358 was considered, with the yields reported in Table 2. The energy required for the pasteurisation of the digestate to
 359 meet PAS10 regulations has not been included in this chain, as it does not directly relate to the production of
 360 the fuel and it could be attributed to the buyer of the fertilizer (digestate).

361 Additional modelling has shown that if the food waste would be shipped to an AD plant 100 km, 200 km,
 362 300 km and 400km far away (instead of the closest one to the DC), the total GHG savings would decrease to
 363 55.3%, 38.5, 21.8% or 5% respectively. This means that the carbon intensity of the FFCG1 pathway is highly
 364 sensitive to the distance between feedstock production and AD plant location.



365
 366 Figure 5. Restaurant food waste to biomethane chain (FFCG1 pathway).

367 3.1.1.3 WTT Emissions of Wooden Pallets to Bioethanol

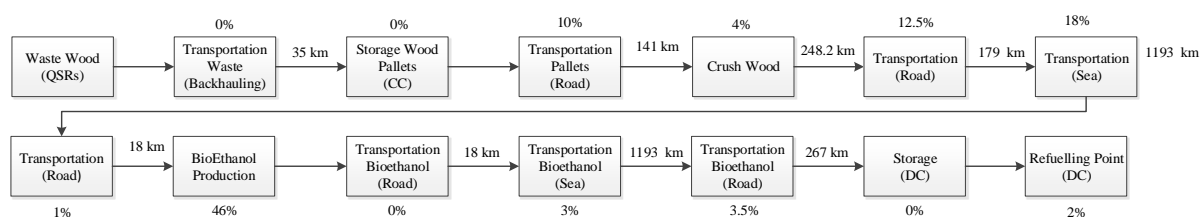
368 Wood waste is mainly generated through wear-and-tear on wooden pallets. Wood waste could be converted into
 369 liquid or gas biofuels through BTL or biomass-to-gas processes, such as Fischer-Tropsch biodiesel (FT Diesel)
 370 and bioDME respectively. Both pathways are very promising with GHG savings of 98% reported from wood
 371 waste to BioDME (BioDME, 2012, Edwards, Larive, 2014) and 97% for wood waste to FT Diesel (Edwards,
 372 Larive, 2014). Producing lingo-cellulosic ethanol from paper and cardboard waste also seems feasible; this was
 373 excluded from the current assessment, however, as no such processing plants were found to operate in Europe.
 374 Only two commercial wood processing plants were found in Europe, as of 2013, capable of producing fuels

375 (bioethanol) and for this reason, all the other pathways for this feedstock were excluded. Bioethanol can be used
 376 in adapted petrol engines; it is also possible to adapt diesel engines to run on 95% ethanol plus a 5% of ignition
 377 enhancing additives (ignition improver, lubricant and corrosion) as developed by Sekab and used in Scania
 378 engines (Sekab, 2013).

379 A carbon intensity of 35.8 g CO₂eq./MJ was estimated and WTT GHG savings around 57% for pathway
 380 WWET1 are suggested. This differs from the 72% GHG savings reported by Edwards, Larive (2014). The
 381 reason is that in the current case, the shipping of wood chips to the locations of the processing plants (Norway)
 382 and bringing the output back represents a high percentage of the overall emissions of the chain. This
 383 performance is below the 60% required to meet the EU sustainability criteria previously mentioned.

384 Figure 6 represents the WWET1 pathway where wasted wood (e.g. wooden pallets) is converted into
 385 bioethanol. In this pathway, it is assumed that wasted wood is stored in the DC, collected by a third party that
 386 crushes the wood into pellets and ships them from the Port of Felixstowe to the Port of Havneholmen (Norway)
 387 by bulk carrier. There, after an 18 km trip, they reach their destination in the Borregaard Synthesis plant where
 388 they could be processed and converted into bioethanol.

389 Despite the fact that using wood pallets from the logistics industry to produce fuels is technically feasible,
 390 it is always better to reuse pallets as emissions from procuring reused pallets are just under 7% of the emissions
 391 of making pallets from primary wood, as stated in Defra (2013b) emission factors. Also, this pathway has
 392 economic implications as removing usable pallets would impact market prices of second hand ones.



393
 394 Figure 6. Wood Waste (pallets) to Bioethanol for the QSRs network of the case study (WWET1 pathway).

395 3.2 Quantifying the Potential Transportation Fuel Generation from QSR Waste Arising Across the 396 UK

397 3.2.1 Main Waste Fractions

398 Based on the case study data obtained from a QSR chain over 3 years, the potential implications for fuel
 399 production from QSR waste arising nationally were estimated (Table 5). The results suggested that British
 400 QSRs and their DCs generate around 24.9 tonnes of waste per outlet each year that can be used to produce fuels.
 401 Cardboard and paper fractions represented over half the tonnage generated, with food waste making up the
 402 second largest fraction with a quarter, and fats and UCO the third with 17% of the total. Plastic represented just
 403 2% of the total tonnage produced.

404 In Table 5, each pathway represents the fuel produced by a specific feedstock and conversion process,
 405 considering the energy yields shown in Table 2 and LHV from Table 6. The total fuel availability has been
 406 converted into GJ to allow an easy comparison of the effectiveness of each pathway and contrast this with the
 407 demand of diesel from British HGVs.

408 When QSRs and DCs separated waste collections and QSRs mixed food waste are consolidated, cardboard
 409 and paper represent over 50% of all weight, food waste a quarter, UCO and fat 17%, wood pallets 4% and
 410 plastics just 2%. Based on the energy content of each feedstock (Table 6), an average restaurant has the potential
 411 to produce 537 GJ of energy per year. From this, cardboard and paper represent around 40% of the total energy,
 412 while UCO and fats rises represent 29%, followed by food waste with 23%, wood pallets with 4% and plastics
 413 with a mere 3%. However these yields are much lower when waste is finally converted into liquid or gas fuels.

414 3.2.2. Energy Yields Scenarios

415 Three scenarios were created showing the kilometres that could be run with waste made from fuel from British
 416 QSRs. These scenarios show the energy content available from each fuel, the distance that could be run with the
 417 vehicles using them and how many HGVs could be powered per year (Table 7).

418 The fuel equivalence of the feedstocks shown in Table 5 is calculated according to three different scenarios
 419 as shown in Table 8. The scenarios represent the outcomes of pathways FFCG1, CACG1, PACG1, WWET1 and
 420 PFSD and PBSF in combination with another two pathways more (TOFA3A and WOFA3a or TOHY1a and

421 WOHY1a) depending on the final use of UCO and fat. In addition to the conversion of paper and cardboard to
 422 biomethane, wood to bioethanol and plastics into synthetic diesel in all three scenarios, the only differences are:

- 423 • Scenario 1 represents the use of UCO and fat to produce FAME biodiesel (WOFA3a, and TOFA3a
 424 pathways).
- 425 • Scenario 2, represents the use of UCO and fat to produce HVO biodiesel (WOHY1a and TOHY1a
 426 pathways) in addition to paper and cardboard to biomethane, wood to bioethanol and plastics to
 427 synthetic diesel.
- 428 • Scenario 3, represents the use of UCO and fat to produce biomethane (WOCG1 and TACG1 pathways)
 429 in addition to paper and cardboard to biomethane, wood to bioethanol and plastics to synthetic diesel.

430 Table 5 Waste-to-fuel potential from British QSRs (assuming 3 DCs for each 1,000 outlets).

Pathway Code	Feedstock	Waste generation per year	Unit	Total GJ (LHV)	Resulting Fuel	Unit	Final Total GJ (LHV)	Fuel
WOFA3a	UCO	120,629	m ³	4,101,387	113,362,870	L	3,753,218	FAME
WOHY1a					45,580,232	L	1,564,314	HVO
WOCG1					52,271,583	kg	2,571,762	Biomethane
TOFA3	Fat (Tallow)	60,612	m ³	2,063,241	56,961,247	L	1,885,873	FAME
TOHY1a					22,902,621	L	786,018	HVO
TACG1					40,500,868	kg	1,992,643	Biomethane
FFCG1	Food Waste	242,586	ton	5,021,524	122,099,674	kg	6,007,304	Biomethane
CACG1	Cardboard	508,224	ton	8,731,290	98,555,880	kg	4,848,949	Biomethane
PACG1	Paper	543	ton	7,144	54,019	kg	2,658	Biomethane
WWET1	Pallets	42,182	ton	780,364	8,642,498	L	183,905	Bioethanol
PFSD	Plastics (Film PP)	9,190	ton	404,366	8,638,136	L	296,461	Synthetic Diesel
PBSD	Plastics (HDPE)	6,135	ton	269,951	5,766,745	L	197,915	Synthetic Diesel

431

432 Table 6 Energy content of different feedstocks.

Product	LHV	Unit	Source
Typical Diesel	43.10	GJ/tonne	Edwards, Larive (2014)
FAME	33.11	GJ/m ³	Edwards, Larive (2014)
HVO	34.32	GJ/m ³	Edwards, Larive (2014)
Biomethane	49.20	GJ/tonne	Edwards, Larive (2014)
Bioethanol	21.28	GJ/m ³	Edwards, Larive (2014)
Synthetic Diesel	34.32	GJ/m ³	Edwards, Larive (2014)
UCO (refined oil)	34.00	GJ/m ³	Edwards, Larive (2014)
Fat (Tallow)	34.04	GJ/m ³	Edwards, Larive (2014)
Food Waste	20.70	GJ/tonne	Banks and Zhang (2010)
Cardboard	17.18	GJ/tonne	Banks and Zhang (2010)
Paper	13.16	GJ/tonne	Banks and Zhang (2010)
Pallets (Wood Logs)	18.50	GJ/tonne	Edwards, Larive (2014)
Plastics (Film PP)	44.00	GJ/tonne	Themelis and Mussche (2014)
Plastics (Bottles HDPE Natural)	44.00	GJ/tonne	Themelis and Mussche (2014)

433

434 Assuming that each HGV runs 85,000 miles/year (136,794 km) and an average fuel consumption for
 435 biomethane lorries of 25.3 kg/100km (17.1 MJ/km), 32 L/100km (10.6 MJ/km) for diesel and biodiesel lorries,
 436 and 86.9 L/100km (18.5 MJ/km) for bioethanol fuelled trucks, it has been estimated that the main waste

437 feedstocks of the FFSC would be enough to run between 910 and 1,221 million km per year. This means that
438 between 6,659 and 8,928 HGVs could be powered with fuels from waste streams (Table 8). Excluding PFSD
439 and PBSB pathways from these values due to their lack of GHG savings, British fast food fleets could run
440 between 864 and 1,174 million km per year with very low carbon fuels, this is between 6,317 and 8,587 HGVs
441 depending on the scenario chosen, these numbers are considerably superior to the number of HGVs distributing
442 to QSRs in Great Britain.

443 In Scenario 1, the conversion of UCO and burger fat into FAME biodiesel yields 5.6 million GJ, more than
444 double compared to when the same feedstocks are converted into HVO biodiesel in the second scenario. In this
445 scenario, the conversion of feedstocks into FAME biodiesel (B100), biomethane and bioethanol, yields the
446 largest energy production of all three scenarios with over 17 million GJ, enough to drive almost 1.2 million km
447 with renewable fuels. Under scenario 2, UCO and fat are converted into second generation biodiesel (HVO).
448 Under this scenario, 6,659 vehicles could run with a mix of different fuels. As the conversion efficiency is
449 lower, scenario 2 presents the lowest energy yield of all three scenarios with 3.3 million GJ/year less energy
450 than scenario 1 and 2.2 GJ/year than scenario 3.

451 Scenario 3 was developed after interviews conducted with truck manufacturers who indicated that new sales
452 of HGVs from January 2014 had to meet the Euro 6 emission standard and that these vehicles would see their
453 warranty made void if vehicles use biodiesel in concentrations exceeding the EN590 standard (DAF Trucks
454 Ltd., 2013, Mercedes-Benz, 2013, Volvo Trucks, 2013). This means that concentrations beyond 7% of FAME
455 biodiesel or 30% of HVO biodiesel are not allowed in Euro 6 trucks. If the FFSC wants to convert all waste
456 streams into transportation fuels and consume all of it, scenario 3 represent the only alternative. In the other
457 scenarios, the production of fuel exceeds the potential demand of Euro 6 vehicles owned by the FFSC. In this
458 scenario, UCO and fat are co-digested to produce biomethane. This approach would yield 15.4 million GJ of
459 biomethane; enough to run 898 million km/year and power 6,566 biomethane vehicles in addition to the yields
460 of bioethanol and synthetic diesel common to all three scenarios.

461 Ethanol is a fuel that is found in concentrations of up to 10% in European conventional petrol following the
462 EN228 fuel standard. It is also possible to use pure ethanol in some engines. It is estimated that such alternative
463 would produce enough power trucks for almost 9.9 million km or 73 trucks per year. As bioethanol has a lower
464 energy intensity than biodiesel, long haul routes may require larger fuel tanks which could potentially impact on
465 the vehicle payload. As previously mentioned, bioethanol can also be used in diesel engines with the addition of
466 certain additives.

467 The use of plastics common to all three scenarios could power 341 HGVs each year. However, this would
468 not lead to GHG savings as plastics are made from fossil hydrocarbons. Furthermore, it is difficult to guarantee
469 that only end of life plastics are used. As procuring virgin plastic is more expensive and carbon intensive than
470 recycling it, the GHG emissions of pathways PFSD and PBSB are likely to increase carbon emissions and
471 plastic prices if not managed well.

472 3.2.3. WTW GHG Emissions

473 Since October 2013, the Companies Act 2006 Regulations 2013 oblige all UK quoted companies to report on
474 their GHG emissions (Defra, 2013b). Based on the UK Government methodology for company reporting (Hill,
475 Venfield, 2013), assuming that the fleets are owned or controlled by the logistics operators, and using the
476 emission factors reported in Table 4, the carbon emissions and savings for each scenario have been calculated
477 as appear in Table 8.

478 Scenario 1 produced the most energy and therefore could displace more conventional diesel, producing
479 higher GHG savings. Scenario 1 indicates that replacing 17.1 million GJ of conventional diesel for biodiesel,
480 biomethane and bioethanol would reduce GHG emissions by almost 900 thousand tonnes of CO₂eq. per year
481 (almost 32% less). Similarly, scenario 2 shows savings of almost 652 thousand tonnes per year (36% less).
482 Scenario 3 shows that 671 thousand tonnes per year (over 40% less than using conventional natural gas) could
483 be saved by using most of the waste feedstocks to produce biomethane. This suggests that Scenario 1 will yield
484 the highest carbon savings overall. Looking at the carbon intensity of each scenario normalising to tonnes of
485 CO₂eq./GJ, Scenario 1 carbon intensity is the lowest of all three scenarios with 24.1 kg CO₂eq./GJ (Table 9).

486 Detailed data regarding the fuel consumption of QSR distribution fleets in British districts is unavailable.
487 Extrapolating the number of vehicles of the case study and in addition considering that Euro 6 diesel vehicles
488 can only use low percentages of biofuels, it is evident that the fuel potential production from wastes from the
489 British FFSC exceeds its demand.

490 Table 7 Potential energy produced from wastes, km replaced with alternative fuels and number of vehicles powered by these (assuming 136,000 km year⁻¹). Quantities are in
 491 litres, except biomethane that is in kg.

Fuel	Scenario 1 - UCO/Fat to FAME B100				Scenario 2 - UCO/Fat to HVO B100				Scenario 3 - UCO/Fat to Biomethane			
	Potential Production	GJ	Million km	Vehicles	Potential Production	GJ	Million km	Vehicles	Potential Production	GJ	Million km	Vehicles
Biodiesel (L)	170,324,117	5,639,091	532.3	3,891	68,482,853	2,350,332	221.8	1,622	-	-	-	-
Biomethane (kg)	220,709,573	10,858,911	632.4	4,623	220,709,573	10,858,911	632.4	4,623	313,482,024	15,423,316	898.2	6,566
Bioethanol (L)	8,642,498	183,905	9.9	73	8,642,498	183,905	9.9	73	8,642,498	183,905	9.9	73
Synthetic Diesel (L)	14,404,880	494,375	46.7	341	14,404,880	494,375	46.7	341	14,404,880	494,375	46.7	341
Total		17,176,283	1,221.3	8,928		13,887,523	910.8	6,659		16,101,597	954.8	6,980

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 493
 494

Table 8 GHG Savings for each scenario

Fuel		Emission Factors (kg CO ₂ eq./GJ)	Scenario 1 - UCO/Fat to FAME B100			Scenario 2 - UCO/Fat to HVO B100			Scenario 3 - UCO/Fat to Biomethane		
			GJ	Scope 1&3 (t CO ₂ eq.)	Savings (t CO ₂ eq.)	GJ	Scope 1&3 (t CO ₂ eq.)	Savings (t CO ₂ eq.)	GJ	Scope 1&3 (t CO ₂ eq.)	Savings (t CO ₂ eq.)
Before	Diesel (average biofuel blend)	88.6	5,639,091	499,623	-	2,350,332	208,239	-	-	-	-
	CNG/LNG	69.3	10,858,911	752,523	-	10,858,911	752,523	-	15,423,316	1,068,836	-
	Petrol (average biofuel blend)	87.1	183,905	16,018	-	183,905	16,018	-	183,905	16,018	-
	Diesel (average biofuel blend)	88.6	494,375	43,802	-	494,375	43,802	-	494,375	43,802	-
			17,176,283	1,311,966	-	13,887,523	1,020,582	-	16,101,597	1,128,656	-
After	Biodiesel	13.6-13.4	5,639,091	76,692	422,932	2,350,332	31,494	176,745	0	0	0
	Biomethane	26.4	10,858,911	286,675	465,847	10,858,911	286,675	465,847	15,423,316	407,176	661,660
	Bioethanol	36.0	183,905	6,621	9,398	183,905	6,621	9,398	183,905	6,621	9,398
	Synthetic Diesel	88.6	494,375	43,802	0	494,375	43,802	0	494,375	43,802	0
Total			17,176,283	413,789	898,177	13,887,523	368,592	651,990	16,101,597	457,598	671,058

495

496 Table 9 Carbon intensity of each scenario (in kg CO₂eq./GJ)

Carbon Intensity	Scenario 1 - UCO/Fat to FAME B100	Scenario 2 - UCO/Fat to HVO B100	Scenario 3 - UCO/Fat to Biomethane
Before	76.4	73.5	70.1
After	24.1	26.5	28.4
Savings	68.5%	63.9%	59.5%

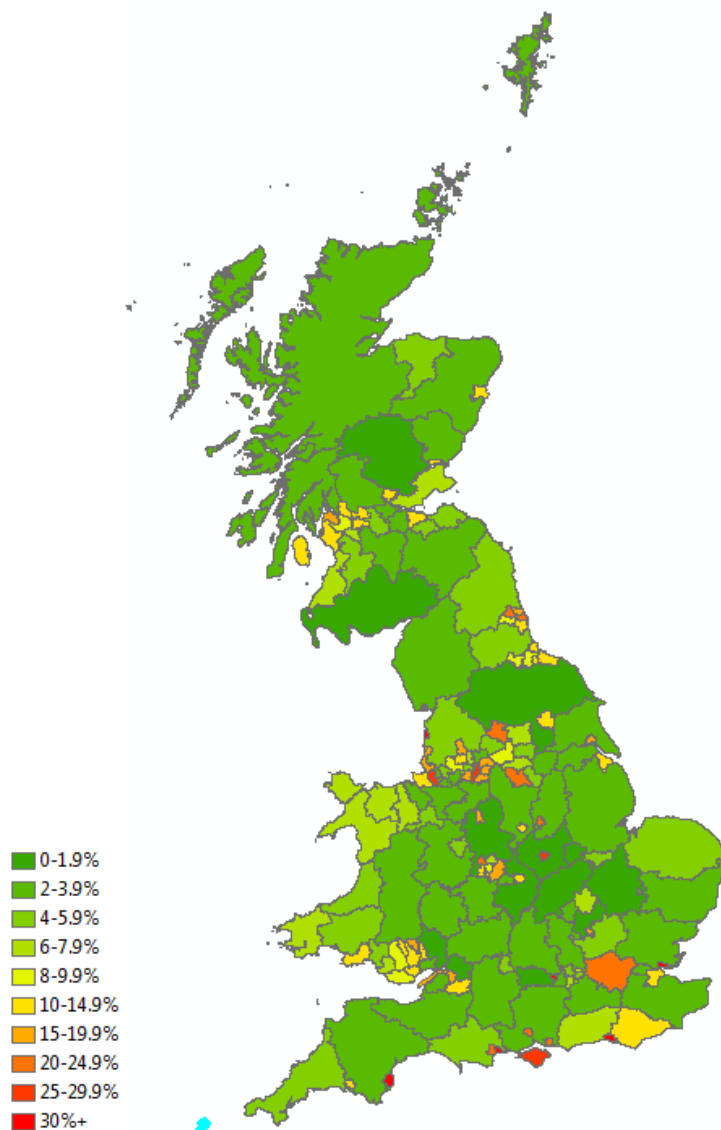
497
 498 The percentage of fuel consumption from HGVs that could be powered by wastes produced by QSRs
 499 according to scenario 1 is shown in Figure 7; this includes the fuel consumption from all British HGVs as
 500 reported by DECC (2013), not just QSR distribution fleets. The fuel consumption of HGVs (excluding buses) in
 501 the UK was around 7 million tonnes in 2011, a quantity that decreased to almost 6.9 in 2012 (DECC, 2013).
 502 Assuming that all HGVs consumed a standard average diesel blend and that the fuel density was 43.1 GJ/t this
 503 translates to a demand of 303.27 and 296.6.5 million GJ in 2011 and 2012 respectively. This indicates that in
 504 2011 around 5.7%, 4.6% and 5.3% of the energy could be supplied by wastes from the FFSC for scenarios 1, 2
 505 and 3 respectively and 5.8%, 4.7% and 5.4% in 2012. If we exclude non-biogenic feedstock, the percentages
 506 were slightly lower at 5.5%, 4.4 % and 5.1% in 2011 and 5.6%, 4.5% and 5.2% in 2012.

507 Based on scenario 1, Table 10 shows the British districts where fuel from waste can provide over 20% of
 508 the energy needs of the area. Greater London presents the highest waste-to-fuel energy output due to the
 509 concentration of 7,313 QSRs. Under scenario 1, London could produce 3.1 million GJ of fuels, representing
 510 24% of the energy needs of the area (13.1 million GJ). This percentage decreases to 19.4% under scenario 2 and
 511 22.5% in scenario 3. Blackpool's waste-to-fuel potential shows that over two thirds of all its diesel consumption
 512 in the district could be covered by fuels from waste streams. At the opposite extreme are the Isles of Scilly
 513 where no QSRs are found and therefore no fuels can be produced.

514 Table 10 Top 20 districts with the highest percentages of energy demand from HGVs' fleets that could
 515 potentially be covered by fuels produced by British QSRs waste each year.

Ranking	District	Num. Outlets	Annual Fuel Potential (in GJ averaged over a 40 months period)	Fuel Demand in 2012 (GJ)	%
1	Blackpool	187	80,780	119,464	67.6
2	Southend-On-Sea	144	62,205	156,288	39.8
3	Reading	139	60,045	161,560	37.2
4	Bournemouth	144	62,205	170,931	36.4
5	The City of Brighton and Hove	259	111,883	330,582	33.8
6	Torbay	104	44,926	149,302	30.1
7	Manchester District	583	251,844	885,212	28.5
8	City Of Leicester	294	127,002	480,631	26.4
9	Isle Of Wight	76	32,830	125,218	26.2
10	Liverpool District	390	168,472	658,621	25.6
11	Newcastle Upon Tyne District	266	114,907	466,053	24.7
12	Greater London Authority	7,313	3,159,070	13,173,082	24.0
13	City of Southampton	192	82,940	354,605	23.4
14	Bradford District	416	179,704	776,637	23.1
15	City of Wolverhampton District	167	72,141	322,485	22.4
16	City of Nottingham	275	118,795	549,733	21.6
17	City of Portsmouth	176	76,028	365,925	20.8
18	Poole	107	46,222	224,029	20.6
19	South Tyneside District	121	52,270	253,625	20.6
20	Sheffield District	531	229,381	1,123,263	20.4

516



517

518 Figure 7 Percentage of the British freight HGVs fuel demand that could potentially be covered by fuels
 519 produced from British QSRs.

520 **4. Discussion**

521 Currently, diesel is the main fuel for UK logistics fleets (Freight Transport Association, 2011) and to fulfil
 522 its GHG reduction targets, the UK Government follows the Renewable Energy Directive by implementing the
 523 Renewable Transport Fuel Obligation. By renewable, the EU means biofuels that deliver at least 60% lower
 524 GHG emissions than conventional fuels, including indirect land use changes. EU policy stipulates that 10% of
 525 energy in the transportation sector will have to come from renewable sources by 2020 (European Commission,
 526 2013). On the other hand, the Euro 6 Directive goal (European Commission, 2011) is to improve air quality by
 527 setting more stringent limits on pollutant emissions. This requires the use of more sophisticated powertrains that
 528 constraint the use of biodiesel, conflicting with the carbon emission goals for transportation. This may bring
 529 forward three unintended consequences. Firstly, as soon as pre-Euro 6 fleets are renewed, biodiesel use may be
 530 diverted from transportation to other uses due to the technical limitations of HGV engines. This is also the
 531 outcome of the discriminatory subsidy structure for renewable fuels set up by the UK Government, where
 532 renewable heating incentives and feed-in-tariffs yield higher returns for energy producers than the benefits
 533 obtained from renewable fuel transport certificates. Secondly, lower biodiesel use will increase HGVs GHG
 534 emissions sharply due to the conflict between GHG and air quality targets. Finally, the market might experience
 535 a shift from dieselisation towards other alternative fuels and technologies. From the pathways evaluated in this
 536 study, it seems that biomethane is the only realistic option for fleet operators meeting Euro 6 emissions and
 537 wishing to reduce GHG emissions at the same time, as these vehicles can deliver enough power and range for
 538 HGVs under long haul duty cycles and the infrastructure for feedstock collection, fuel production and refuelling

539 is well established. In the long run, reducing GHG emissions for specific vehicle classes and duty cycles may
540 also be possible by developing more advanced biofuels and powertrain technologies such as BioDME, dual fuel
541 trucks, hybrid and electric powertrains; however, this will require the deployment of second and third generation
542 waste-to-fuel processing facilities, new refuelling infrastructure, some technology breakthroughs and affordable
543 solutions that might require Governmental support either through subsidisation or favourable policies.

544 Waste management is an area that can give 3PL companies a source of competitive advantage, as their
545 position in their respective supply chains allows them to manage waste collections at a reduced economic and
546 environmental cost. Waste can be consolidated at DCs and used in-situ for producing heat and power or shipped
547 to waste treatment plants where power, heat and fuels can be produced. The economics of conversion of QSR
548 waste into fuel for transportation depends greatly on the density of QSRs, the possibility of guaranteeing a long-
549 term supply of feedstock, the impact of waste reduction initiatives (e.g. efficiency improvements in the supply
550 chain), feedstock and fuel market prices, operational and logistical complexities and Governmental policy and
551 legislation in regards to renewable fuels incentives, carbon quotas and waste treatment.

552 Waste-to-fuel strategies present opportunities to reduce GHG emissions for the whole fast food supply
553 chain while hedging against fuel price volatility and enhancing energy security. In this context, the role of policy
554 makers is critical to establish a level playing field where some biofuels such as biomethane for transportation
555 can compete with other uses. This is paramount when considering that the implementation of Euro 6 emission
556 standards will make it more difficult to reduce GHG emissions for logistics fleets through the use of low carbon
557 fuels, as the options are rather limited. Engine's manufacturers should also consider the potential for fuel
558 production by British QSRs and realise that biodiesel can still play a huge role in the decarbonisation of the
559 logistics sector and that more research and development should be carried out to overcome the technical
560 challenges that Euro 6 brings and developing engines that can tolerate higher concentrations of biodiesel. At the
561 same time, diesel and biodiesel as a fuel for transport seems to present challenges to many British and European
562 local authorities trying to meet EU limits on air quality pollutants. This research suggests that biomethane is a
563 recommendable fuel for road freight as it supports air quality and GHG targets.

564 Alternatively, the feedstocks and fuels presented here can be sold or transferred to other elements of the
565 supply chain (e.g. farms, factories) for heating, cooling and/or power generation where it is possible to take
566 advantage of more favourable governmental incentives (e.g. feed-in-tariffs, renewable heating incentives) than
567 renewable transport fuel certificates. This could also reduce the carbon emissions of the supply chain as a
568 whole; however, the emissions from these other links of the supply chain can be reduced more easily as those
569 depend mainly on the percentage of renewable sources of the British mix grid.

570 **5. Conclusion**

571 The aim of this study was to quantify the waste-to-fuel potential from British QSRs and the WTW emissions of
572 the most feasible pathways based on the waste streams of a major fast food chain. The results indicated that
573 waste from British QSRs could cover the energy needs of between 4.4% - 5.8% of all British HGVs depending
574 on the scenario and year. This translates to around 14-17 million GJ per year. Excluding non-biogenic
575 feedstocks, thousands of vehicles could be powered with renewable fuels obtained from waste streams even if
576 Euro 6 trucks cannot accept high concentrations of biodiesel, by using biomethane instead. As Euro 6 engines
577 can only cope with up to 7% of FAME biodiesel or up to 30% of second generation HVO biodiesel, the surplus
578 generated by the FFSC could be consumed by other national fleets. There is also an opportunity to produce
579 synthetic diesel from plastics; however, carbon savings are unlikely. Risks were also found in the paper,
580 cardboard and pallets waste-to-fuel pathways: Using feedstocks that have not reached their end of life could
581 trigger economic and environmental drawbacks, as the costs and GHG emissions of virgin materials when
582 producing new plastics, paper or pallets are higher than the recycled ones.

583 The reverse logistics of waste collections from QSRs managed by 3PLs show lower carbon emissions than
584 those from dedicated waste fleets. Waste-to-fuel opportunities can become strategically important for 3PLs as
585 a solution to mitigate the volatility of freight energy costs. For 3PLs, waste consolidation can be placed at the DCs
586 and when processing plants are located nearby, carbon emissions and transportation costs become minimal. On
587 the other hand, dedicated waste collection fleets have the flexibility to place DCs in the optimal location to
588 minimise their costs identifying the areas with higher densities of QSRs and the location of processing plants. In
589 both cases, the high capital expenditure of second generation biofuels processing facilities and the uncertainties
590 surrounding British energy policy has resulted in a lack of such facilities in the country, which leads to increased
591 fuel costs and TTW emissions. Since the arrival of Euro 6 HGVs and once older Euro 5 fleets are renewed,
592 diesel fleets will struggle to deliver GHG reduction targets. This may lay the foundations towards a considerable
593 increase on the market share of biomethane HGVs as an alternative to reconcile the air quality and carbon
594 emission agendas.

595 **Nomenclature**

596

3PL	Third Party Logistics Provider	FT	Fischer-Tropsch
AD	Anaerobic Digestion	GHG	Greenhouse Gases
B100	Diesel fuel 100% Biologic Origin	GTW	Grease Trap Waste
BTL	Biomass-to-Liquid	HDPE	High-density Polyethylene
CHP	Combined Heat and Power	HVO	Hydrogenated Vegetable Oil
CNG	Compressed Natural Gas	HGV	Heavy Goods Vehicles
CC	Consolidation Centre	ICE	Internal Combustion Engine
CO ₂ eq.	Carbon Dioxide Equivalent	LDPE	Light-density Polyethylene
CONCAWE	Conservation of Clean Air and Water in Europe	LNG	Liquid Natural Gas
DC	Distribution Centre	QSRs	Quick Service Restaurants
DME	Dimethyl Ether	TTW	Tank-to-Wheel
FAME	Fatty Acid Methyl Ester	UCO	Used Cooking Oil
FC	Fuel Cell	WTT	Well-to-Tank
FFSC	Fast Food Supply Chain	WTW	Well-to-Wheel

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