The Bioeconomy Consultants
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Evidence Gathering for Off-Gas Grid Bioliquid Heating Options

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Author(s):

Lucy Hopwood	Lead Consultant Bioenergy & Anaerobic Digestion, NNFCC
Edward Mitchell	Consultant, NNFCC
Sotirios Sourmelis	Research Analyst, NNFCC
Neil Harrison	Director, re:heat
Steve Luker	Principal Consultant, re:heat

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NNFCC is a leading international consultancy with expertise on the conversion of biomass to bioenergy, biofuels and biobased products.

The Bioeconomy Consultants NNFCC

NNFCC, Biocentre,
York Science Park,
Innovation Way,
Heslington,
York, YO10 5DG

Phone: +44 (0)1904 435182
Fax: +44 (0)1904 435345
Email: enquiries@nnfcc.co.uk
Web: www.nnfcc.co.uk

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Glossary

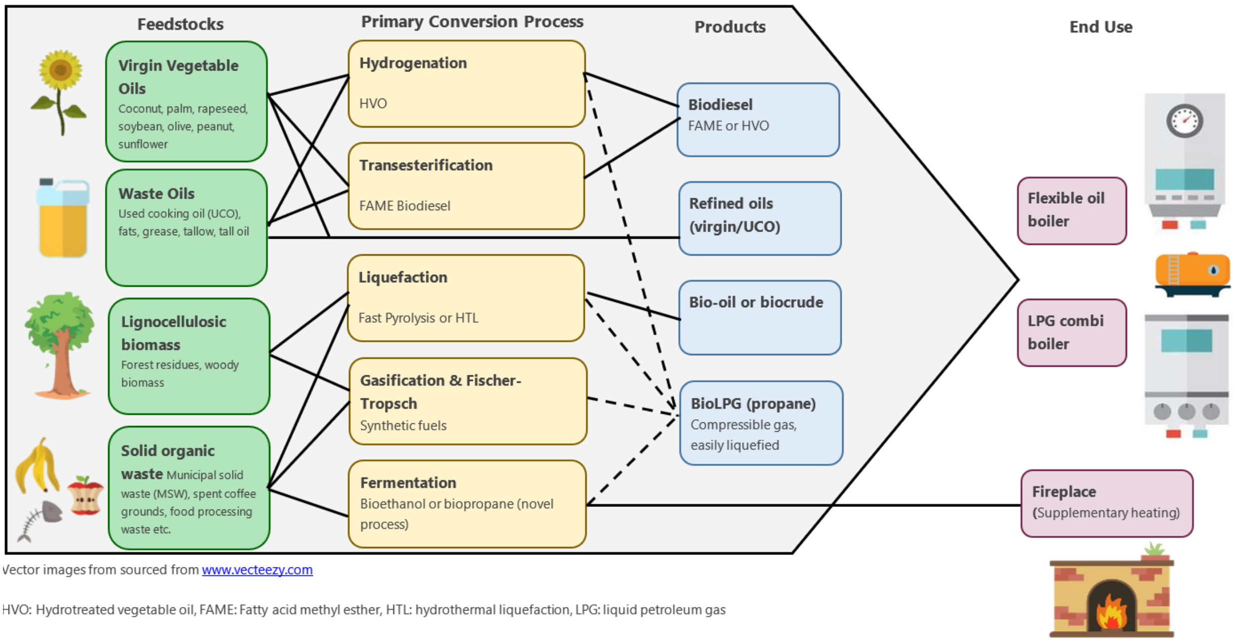
ASTM	American Society for Testing and Materials (standards organisation)
B30K	Bioliquid blends of 30% biodiesel in kerosene
B100	100% biodiesel fuel
BEIS	Department of Business, Energy and Industrial Strategy
BioDME	Dimethyl ether derived from biomass sources
Bioliquid	Liquid product resulting from the thermochemical conversion of biomass. Umbrella term including bio-oil, bio-crude, biodiesel, bioLPG, biopropane, HVO, etc.
BioLPG	Propane derived from biomass sources rather than fossil fuels
BS EN	British Standard and European Standard
CAS	Clean Air Strategy
CfD	Contracts for Difference
CFPP	Cold Filter Plug Point
CGS	The Clean Growth Strategy
Concawe	Association of oil companies carrying out research in environmental science
CV	Calorific value
DECC	Department of Energy and Climate Change (former)
DfT	Department for Transport
DUKES	Digest of United Kingdom Energy Statistics
EPC	Energy Performance Certificate
ErP	Energy-Related Products Regulations
FAME	Fatty acid methyl ester. Type of biodiesel obtained by transesterification of vegetable oils
FAO	Food and Agriculture Organisation of the United Nations
FPBO	Fast pyrolysis bio-oil
FPS	Federation of Petroleum Suppliers
FT	Fischer-Tropsch; process for producing synthetic fuels
GB	Great Britain
GHG	Greenhouse gas
HMT	Her Majesty's Treasury
HVO	Hydrogenated vegetable oil
ICCT	International Council on Clean Transportation
Kerosene	Also called heating oil or kero
kWh	Kilowatt hour. Unit of energy equal to 3.6 MJ
LPG	Liquid Petroleum Gas (mostly propane with small amounts of butane and other hydrocarbons)
MCS	Microgeneration Certification Scheme
MJ	Megajoule. Unit of energy equal to 0.278 kWh
NAEI	National Air Emissions Inventory
NAPCP	National Air Pollution Control Programme
NOx	Oxides of nitrogen
OECD	Organisation for Economic Co-operation and Development
OFS	OFTEC Specification
OFTEC	The trade association for the oil heating industry in UK and Ireland
OGG	Off-Gas Grid
PM	Particulate matter
REACH	Registration, Evaluation and Authorisation of Chemicals classification system
REDII	Renewable Energy Directive, second iteration
RHI	Renewable Heat Incentive
ROS	RTFO Operating System
RSPO	Roundtable on Sustainable Palm Oil

RTFC	Renewable Transport Fuel Certificate
RTFO	Renewable Transport Fuels Obligation
SAP	Standard Assessment Procedure. Used to assess and compare the energy and environmental performance of dwellings
SEDBUK	Seasonal Efficiency of a Domestic Boiler in the UK. Replaced by the Product Characteristics Database on the Building Energy Performance Assessment website.
SO_2	Sulphur dioxide
SVO	Straight vegetable oil i.e. used directly as a fuel without processing.
Tall oil	Viscous yellow-black liquid obtained as a co-product of the process of pulp and paper manufacturing. Also referred to as liquid rosin or tallol
TSA	Tank Storage Association
UCO	Used cooking oil
UCOME	Used cooking oil methyl ester
UKLPG	Trade association for the LPG industry in the United Kingdom.

Executive Summary

The decarbonisation of space and water heating is one of the greatest challenges within the UK energy landscape. Domestic properties that are off the gas grid emit over 7 million tonnes of greenhouse gases (CO_2-equivalent) to the atmosphere each year and present a unique opportunity to implement renewable heating technologies and reduce dependency on fossil fuels.

Bioliquids are liquid fuels manufactured from a renewable biological source such as virgin or used vegetable oils, woody biomass and energy crops. The key bioliquids of interest here are virgin vegetable oil, used cooking oil, biodiesel, BioLPG (biopropane) and blends of biodiesel and fossil fuels. Despite there being an established market and support mechanism for biofuels in the transport sector, bioliquids used for heat in boilers are not currently eligible under the RHI.



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HVO: Hydrotreated vegetable oil, FAME: Fatty acid methyl esther, HTL: hydrothermal liquefaction, LPG: liquid petroleum gas

The work presented here is the result of an evidence gathering exercise on the potential of bioliquids for use as heating fuels in off-gas grid properties. The work draws upon published literature and policy documents, structured stakeholder interviews, a field-based survey, and a deployment model in order to better understand the costs, constraints and impacts of using neat bioliquids or blends.

Overview

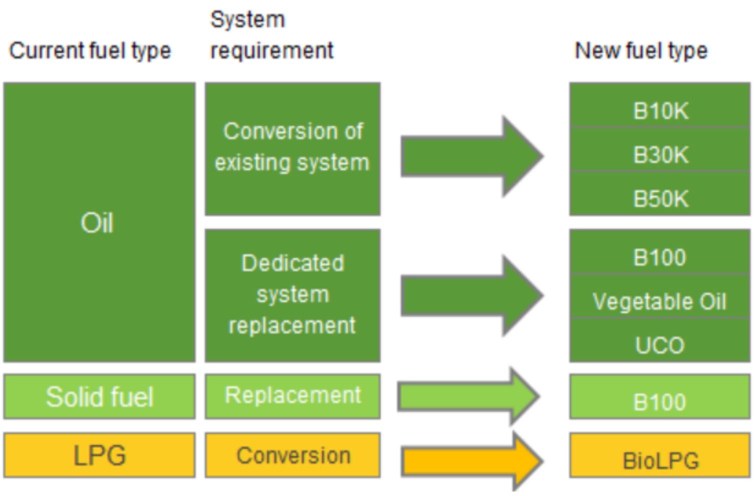
There are over 4 million homes in Great Britain that do not have access to the national gas grid and therefore rely on bulk deliveries of fuels once or twice per year for their primary source of heating. The majority, 1.1 million, use home heating oil or kerosene but there are also 193,000 that use liquid petroleum gas (LPG) and 200,000 that use solid fuels such as coal.

The market presents a significant commercial opportunity whereby the value of off-gas fuels used in this sector is £1.1 billion. Typical fuel prices are 3.8 p/kWh for heating oil and 6.5 p/kWh for LPG, with a higher proportion of off-gas grid homes being classified as in fuel poverty compared to those that are on the gas grid. In order to facilitate the use of bioliquids in these properties, in some cases a new dedicated boiler and ancillary equipment such as tanks and pipework, will be required and in other cases the homeowner can retain their existing system and use a blend of a bioliquid and heating oil.

Conversion of existing boilers to use blends

A review of evidence presented suggests that oil-fired boilers less than 5 years old should be compatible with a blend of up to 30% biodiesel in kerosene (B30K), depending on the boiler manufacturer and the burner installed. A blend containing 30% biodiesel represents a step change in that higher blend ratios may begin to cause technical problems such as deposit build-up on burner heads, reduced boiler lifetime and failing seals, filters and pumps. Many of these issues are the result of biodiesel coming into contact with materials which are incompatible with the fuel. The fuel handling requirements are generally well-understood from previous field trials and from guidance documents. As a result of these issues, blends with greater than 30% biodiesel are likely to require a new dedicated B100 boiler as well as a new integrally bunded fuel storage tank.

Boilers older than 5 years old are likely to require a conversion kit in order to use a biodiesel blend up to B30K. However, some systems may not be suitable for conversion so an assessment would be required by a qualified heating engineer. If conversion is possible, the cost of the kit and installation is estimated to be £500-£1000.



100% biodiesel boilers

The technical capability of dedicated boilers to use biodiesel has been well demonstrated and there have been several examples where biodiesel has been used for heating at the commercial scale. Boiler capability has been less well proven at the domestic scale (<50 kW) and few manufacturers currently offer a dedicated 100% biodiesel (B100) system. This is, however, largely a result of market constraints rather than technical constraints. One of the key differences between B100 boilers and oil-fired boilers is the materials used. Guidance is available on compatible materials which include stainless steel, Teflon™, Nylon and Viton® seals. A pre-heater may also be required prior to the burner to ensure efficient combustion of the fuel, depending on the type of biodiesel.

The feedstock used to produce biodiesel impacts the cold weather performance and the lifecycle greenhouse gas emissions of the fuel. Feedstocks such as tallow produce a fuel that may crystallise during periods of cold weather, which can lead to blockages in the boiler supply lines. Feedstocks with the most preferential cold weather properties include rapeseed and sunflower oil.

Over 800 million litres of biodiesel are consumed in the UK transport sector each year, most of which is derived from used cooking oil (UCO). Typical biodiesel costs are 7-9 pence per kWh of fuel energy.

The evidence presented suggests that emissions of particulate matter (PM) and sulphur dioxide (SO_2) may be reduced for B100 and B30K compared to kerosene heating oil, but there are mixed findings with regard to carbon monoxide (CO) and nitrogen oxides (NOx) emissions.

Virgin and used-cooking oil boilers

From the limited amount of evidence available, whilst it is technically possible to burn virgin vegetable oils such as rapeseed oil, sunflower oil and soybean oil in boiler systems, there are significant barriers to the large-scale use of these bioliquids for domestic heating. In comparison to biodiesel, the low calorific value, high viscosity and adverse cold weather properties of vegetable oils are likely to require additional infrastructure such as a heated tank, heated supply line and large pre-heater before the burner. UCO would also require significant cleaning and filtering in order to avoid blockages in the system. Whilst there are several manufacturers of waste oil boilers, maintenance costs would be higher than for conventional systems and boiler longevity may be reduced.

Large volumes of vegetable oils are available but legislation such as the second iteration of the Renewable Energy Directive (REDII) is likely to reduce the demand for crop-based biofuels which may be in direct competition with food crops. Large volumes of UCO are also available and this is the key feedstock used to produce biodiesel consumed under the Renewable Transport Fuel Obligation (RTFO). UCO-biodiesel is currently imported from over 70 nations worldwide and imports are growing rapidly from countries such as China in response to increased demand in the transport sector, following increases in the RTFO biofuel content requirements. Going forward it is likely that biodiesel availability will be constrained by competition from the transport sector in the short term, but in the long-term availability may increase with the electrification of vehicles and the scaling up of development fuels such as E-fuels.

BioLPG boilers

BioLPG or biopropane can be used directly in place of fossil-LPG as a drop-in fuel and therefore properties do not require a new dedicated boiler to use this fuel. BioLPG is already commercially available in the UK and Ireland through one supplier, and other suppliers are investing in developing new supply chains. Propane is a by-product of several biomass conversion processes including the hydrotreating of vegetable oils (HVO) which is currently the only route for BioLPG in the UK. HVO production is increasing in Europe and therefore BioLPG availability is likely to increase, though there may be competition from the industrial sector where LPG is used for several processes. BioLPG currently costs approximately 22% more than fossil LPG, though prices are likely to reduce in the future.

Key benefits of LPG heating systems include low emission factors for air pollutants such as particulate matter, carbon monoxide and sulphur dioxide. LPG is a gas at the point of combustion and therefore emissions are low. The greenhouse gas emissions savings of BioLPG are more variable since it is highly dependent on the source process and feedstock supply chain, with a reported range of 18 to 180 kg of CO_2-equivalent per MWh of fuel energy.

Storage and handling

LPG tanks are pressurised steel vessels and are typically owned by the fuel supplier rather than the homeowner, who pays a standing charge for tank maintenance. BioLPG does not require any amendments to the fuel storage system or supply lines.

In contrast to LPG, proprietors of dwellings using kerosene heating oil usually take ownership of the tank and are responsible for its maintenance. Tanks are typically plastic with a volume of 1500-3500 litres and can be single skinned or integrally bunded. Evidence has suggested that existing oil tanks should be capable of storing a biodiesel blend of B10K and possibly up to B30K, after which a new dedicated tank would be required. New B100 tanks should be integrally bunded and approximately half the size of current oil tanks in order to increase fuel turnover, costing £1000-2000. When converting a property to use a blend up to B30K, it is required to drain and clean the tank as biodiesel can interact with contaminants such as sludge and moisture.

Innovative fuels

A number of novel development fuels have been discussed including fast pyrolysis bio-oil, hydrothermal liquefaction biocrude and gas-to-liquid technologies for the production of biokerosene. The evidence presented suggests that bio-oil and biocrude are not suitable for domestic applications without upgrading due to their fuel properties, although they have been used in larger scale commercial boilers. The pursuit of novel processes for the production of biokerosene and synthetic kerosene for the aviation sector may compliment the decarbonisation of off-gas grid heating, particularly since the two sectors have opposing seasonal peak demands, but the technology has yet to move beyond demonstration stage.

Bioliquids could make a significant contribution to the UK domestic heating sector, but capacity limits within the supply chain are likely to be the main constraints on development. The import, production, storage, handling and distribution of multiple bioliquid fuel options could cause confusion within the domestic sector, so offering a limited number of fuel options and providing clear guidance would be essential. Installation costs and carbon savings are well documented and understood; however, further work is necessary to quantify air quality benefits, to review maintenance costs and to better understand the compatibility of converted or replacement systems with a broader range of fuel types.

Cost comparisons

The costs of conversion have been evaluated based on housing archetype and existing fuel type. The lowest conversion cost is from a fossil LPG system to a BioLPG system, where the homeowner can retain their existing boiler and tank with no modifications necessary since BioLPG is a drop-in fuel. The only increases in cost are likely to be from the fuel premium for BioLPG, which is estimated to be 22% more than fossil LPG.

The second lowest cost scenario is the conversion of existing oil-fired heating systems with boilers that have been installed within the last 3-5 years. Most burners fitted in these newer boilers are compatible with a blend up to B30K and the only work required would be a visit by a qualified service engineer to adapt the burner operating conditions to the new fuel. The cost of this could be similar to a routine annual service (£100), or up to £350 if a replacement burner head is required. Systems with an older fuel tank will also need to have the fuel tank cleaned and flushed and the total estimated cost in this case is £650. With additional modifications to the fuel oil feed system, the cost could reach £1000 and if a new tank is required the total cost could reach £2925. Boilers older than 5 years are likely to require replacement for B30K blends and above, at a cost of £3025 without a tank and £5950 with a new tank. Annual maintenance costs for a B100 system are expected to be up to 3 times higher than a kerosene-fired system at the current time due to increased rates of replacement for routine parts and potential issues with fuel degradation.

1 Introduction

Heating accounts for 47% of total final energy consumption in the UK [1]; 55% of which is accounted for by the domestic sector, mostly for space heating, but also for hot water and cooking. In UK households, a total of 376.6 TWh was used for heating and hot water alone in 2017. The best and most cost-effective way to reduce emissions from domestic heating is to make our homes better insulated and more energy efficient. However, there is also a need to promote a shift to the use of low carbon fuels in the generation of our domestic heat as just 7.7% of heating and cooling was derived from renewable sources in 2017, up from 4.0% in 2013 [2].

The UK has been working to decarbonise the heat sector since the introduction of the Renewable Heat Incentive (RHI) Scheme in 2011. The aim of the scheme was to accelerate deployment by providing a financial incentive to homes and businesses to install renewable heating systems. The Domestic RHI was introduced in April 2014 to support domestic properties in switching to renewable heating; eligible technologies are air source heat pumps, ground source heat pumps, biomass boilers and solar thermal panels. The RHI scheme delivered 825.6 MW of new installed renewable heat capacity in the period from April 2014 to December 2018. The current RHI budget is set to the end of financial year 2020/21 with the future of the scheme, along with wider support for renewables and low carbon energy options, being the subject of, or a feature within, a number of policy reviews at the time of writing.

The Clean Growth Strategy (CGS) and subsequent Future Framework for Heat in Buildings Call for Evidence [3] described the ambition of The Department for Business, Energy and Industrial Strategy (BEIS) to phase out the installation of high carbon fossil fuel heating in new and existing off-gas grid residential buildings as part of a wider plan to decarbonise the UK economy further through the 2020s. Although phasing out high carbon fossil fuel heating will be a challenge, it is also seen as an opportunity to offer new jobs, new skills, and investment in innovation, as well as greater comfort and convenience for our households and businesses.

In May 2018 the draft Clean Air Strategy [4] discussed the need for action to safeguard our health and set out measures and aims to improve air quality over the next decade. Since the middle of the 20th century many of the worst impacts of air pollution have been addressed through regulatory frameworks, investment by industry in cleaner processes and a shift in the fuel mix towards cleaner forms of energy. Phasing out of coal and oil-fired heating will ensure this transition improves air quality whilst at the same time reducing carbon.

This work has been commissioned by BEIS to gather evidence on the technical and market potential of bioenergy options for off-gas grid heating for which less evidence is currently held, namely bioliquids and bioLPG (biopropane). The scope extends to domestic boilers in existing housing-stock in England and Wales only, as previous work has focussed on the characteristics of bioliquids for non-domestic heating [5]. The report has been prepared through a combination of literature review and stakeholder engagement. Section 3 and 4 outline the technology and fuel options respectively, describing compatibility and availability issues, costs and constraints. The practical constraints and costs of installation were identified through a short field-based survey, the findings of which are described in section 5. The scale of the opportunity, key challenges and their potential impact are then discussed in more detail in section 6.

1.1 Off-gas grid heating in the UK

There are an estimated 26 million homes in Great Britain, of which 4 million homes are off the gas grid [6]. The predominant domestic heating fuel in all homes is natural gas – used for space heating, hot water and cooking. Currently, over 80% of domestic heating is provided by over 20 million gas boilers; largely a result of the creation of the national gas distribution network [6][7]. Around 0.5 million homes are connected to district heating systems, and for the remaining housing stock, the primary fuels used for space and water heating are electricity, heating oil (kerosene), liquefied petroleum gas (LPG) and gas oil, with some wood, coal and other solid fuels. Domestic heating systems are typically replaced at a rate of 5-7% per annum, which equates to approximately 1.2 million gas boilers for natural gas-fired systems [7].

Table 1: Number and proportion of GB households by main space heating fuel 2015 [6]

	England		Scotland		Wales		GB	
	(000's)	(%)	(000's)	(%)	(000's)	(%)	(000's)	(%)
Mains gas	19,229	85	1,870	78	995	79	22,094	84
District heating	396	2	25	1	5	0	426	2
LPG	147	1	21	1	25	2	193	1
Heating oil	821	4	140	6	143	11	1,104	4
Solid fuel	137	1	26	1	37	3	200	1
Electricity	1,853	8	316	13	63	5	2,231	8
Other / Unknown	0	0	4	0	0	0	4	0
TOTAL	**22,583**	**100**	**2,402**	**100**	**1,268**	**100**	**26,254**	**100**

Northern Ireland has the largest percentage of homes using heating oil in Western Europe, with 68% of homes (84% in rural areas) relying on kerosene for their primary source of heating [8]. Natural Gas was first introduced to Northern Ireland in 1996 and as of June 2018, 209,000 customers have been connected to natural gas [9]. Gas network extension is supported by the Strategic Energy Framework 2010, but there were an estimated 526,190 homes using heating oil in 2016 [8].

1.1.1 Fuel types

This section provides a brief technical overview of the common off-gas grid fuel types that could be replaced by bioliquid heating technologies, relevant regulations and standards, and a basic insight into the current market size and common issues.

Heating oil

Kerosene is also known as Class C2 heating oil, 28 second burning oil, industrial paraffin and kero. It is a clear to amber liquid and is produced in large volumes through fractional distillation of crude oil, containing mostly C12 to C18 hydrocarbons. Kerosene quality is assured by standards such as at BS EN 2869:2017 and ASTM D3699-18a, which categorise fuel grades into classes. Class C1 is labelled as paraffin which is high grade kerosene, with a lower sulphur content and higher smoke point than Class C2. Class C2 is labelled as kerosene which is of the type used in domestic and commercial boilers.

Higher sulphur content increases the lubricity of the fuel. The Sulphur Content of Liquid Fuels (England and Wales) (Amendment) Regulations 2014 requires home heating oil to have a maximum sulphur content of 0.1%, whilst jet fuel is restricted to 0.3% in accordance with Standard 91-91. Additives are typically required for kerosene which is to be used for cooking in appliances such as an AGA Rangemaster.

Data is widely available for the domestic production, import and export of oil and refinery products in the UK, including kerosene. Total net supply of burning oil was 3.172 million tonnes in 2017 which has been fairly stable over the last ten years, only exceeding 4 million tonnes in 2006 and 2010 (DUKES table 3.2). Of the 3.172 million tonnes (3.96 billion litres), 2.047 million tonnes were produced indigenously, 0.562 million tonnes imported, and 0.102 million tonnes exported. All imported burning oil was sourced from the EU in 2017, with over 75% coming from the Netherlands (DUKES table 3.9). In the same year, kerosene consumption in the residential sector was 1.9 million tonnes and in the aviation sector was 11.8 million tonnes [2]. Despite small differences in the composition of kerosene burned in domestic installations and aircraft, there is a trade-off in seasonal demand in the two sectors which offers some protection against seasonal price fluctuations, as shown in Figure 1.

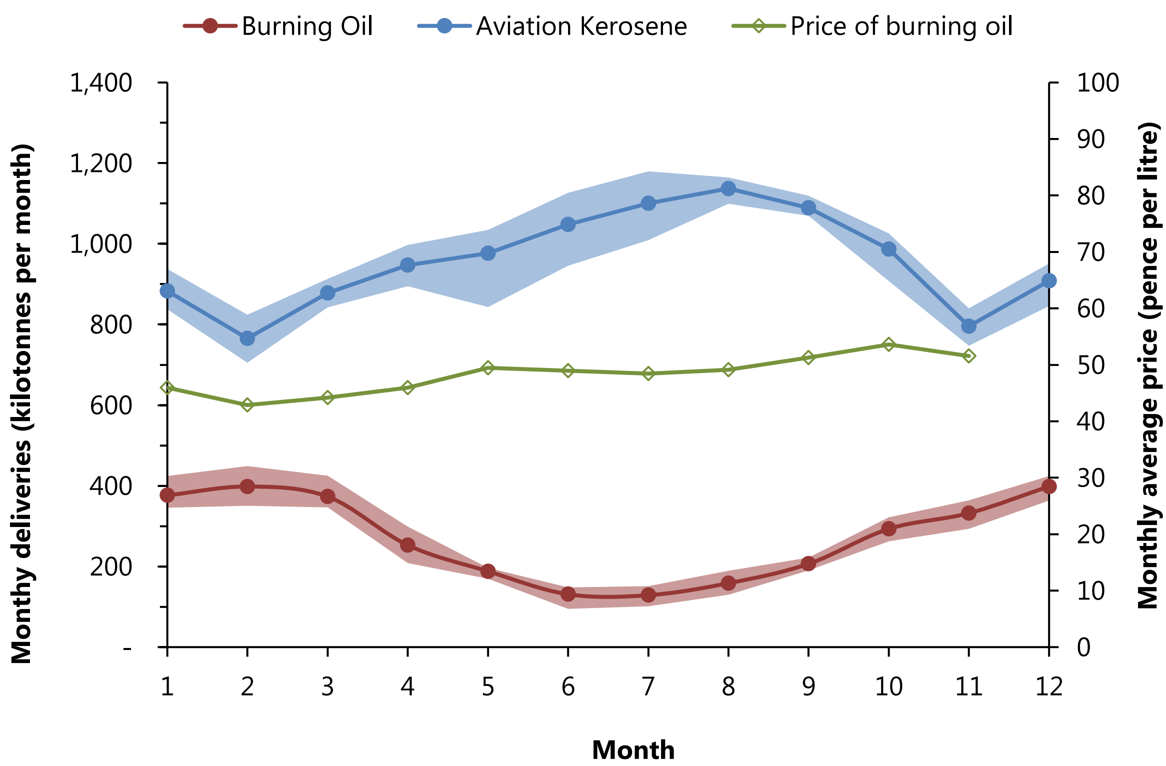


Figure 1. Seasonal demand for aviation kerosene and home heating oil kerosene. Shaded area shows the range over a 5-year averaging period 2014-2018. Data sourced from BEIS [11][12].

<u>LPG</u>

Liquefied Petroleum Gas (LPG) consists of a number of flammable hydrocarbon gases that are liquefied under mild pressurisation (2 bar for butane and 7 bar for propane at 15°C). The major constituent of bulk LPG for domestic purposes is propane (C_3H_8) since it has a lower boiling point and higher storage pressure than butane (C_4H_{10}), which is more commonly used in indoor environments.

LPG is versatile and widely used around the world for a variety of applications other than domestic and commercial heating, such as for transportation and cooking.

The UK LPG market is mature for both heating and industrial use. In 2017, 61% of LPG consumed in the UK was for non-energy use [2]. The residential and commercial/public sectors accounted for 7% (200,000 tonnes) and 13% (362,000 tonnes) of LPG consumption respectively [2]. Combined UK production and imports of LPG has increased from 2.2 million tonnes in 2001 to 3.0 million tonnes in 2017 (5,727 million litres) [10]. Over 54% of LPG imports were sourced from Norway in 2017.

A 2006 report by the Competition Commission (now the Competition and Markets Authority) found that four suppliers supply 90% of the domestic bulk LPG market [13], whereas the largest ten heating oil suppliers supply <50% of the home heating oil market [14].

Gas oil

Gas oil is a middle distillate fuel, also known as red diesel or 35 second burning oil. It is used for a variety of low duty applications including construction and agricultural machinery, and marine vessels. It is also used as a heating fuel, more commonly in the commercial sector than the domestic, and is classified as Class A2 or Class D fuel under BS2869:2017. In 2017, gas oil consumption in the domestic and commercial/public administration sectors was 0.14 million tonnes and 0.68 million tonnes respectively [2].

The outcome of a Call for Evidence on the use of rebated gas oil or red diesel was published in July 2018 [15]. It found that Gas oil accounts for over 15% of total diesel use and although the use of gas oil for heating has declined, it is still used in off-grid commercial, public sector and agricultural buildings to provide heat. Gas oil intended for uses other than diesel engine road vehicles (DERV) is entitled to a rebate of 46.81 pence per litre giving an effective rate of 11.14 pence per litre. Whereas there are currently no seasonal requirements for kerosene under BS 2869:2017, the maximum cold filter plugging point (CFPP) for gas oil is -4°C from March to October and -12°C from October to March. Gas oil may contain up to 7% Fatty Acid Methyl Ester (FAME) biodiesel which meets the requirements of BS EN 14214.

Solid fuel

The term 'Solid Fuel' covers both coal and coal-derivatives which are referred to as "Manufactured Fuels". Manufactured fuels used in a domestic context include coke, breeze and assorted smokeless fuels. According to DUKES 2018 [2], the largest single use of coal outside of power generation was the manufacture of mineral products (5.10 TWh), with domestic use close behind at 4.56 TWh which is equivalent to 571,000 tonnes of coal. Manufactured fuel use totalled 2.01 TWh, and domestic heating is the only use for these products outside the steel manufacturing industry.

Coal and manufactured fuels are typically burnt in open fires; open fires with back boilers (which typically provide heat to the room in which they are situated, a limited number of radiators and possibly a domestic hot water tank); and enclosed stoves. These appliances range from ~25% to ~80% efficient. One leading manufacturer of domestic solid fuel boilers in the UK is Trianco which offers boilers in the range 13-23 kW, costing £1,980-2,580 including VAT. The average retail price index (RPI) was 38.0 pence per kg for coal and 45.0 pence per kg for smokeless fuel in April 2019.

Coal and manufactured fuels remain a significant source of heating in rural areas in the UK, predominantly in former coalfield areas, such as Fife and Ayrshire in Scotland, South Wales and the East Midlands and North East of England. In these areas, there is a strong social connection with the use of solid fuels, and it is relatively common for former miners to have coal provided for little or no cost as part of their pension arrangements.

Some manufactured fuels also include a biomass fraction as companies respond to market drivers and work to improve the environmental credentials of their products.

1.1.2 Economics and Fuel Poverty

The average monthly retail price of kerosene heating oil for the year 2018 is shown in Figure 1, using data from BEIS [12]. The retail price can vary on a daily or weekly basis and between suppliers, leading to consumers carefully selecting the date on which to place an order. From a high of 55.7 pence per litre in January 2014 (£695/tonne), the retail price reached a low of 21.9 pence per litre in February 2016 (£273/tonne).

The BRE Standard Assessment Procedure (SAP) for Energy Rating of Dwellings (SAP 10.0) [16] gives a useful comparison of fuel costs for different heating fuels, though these values are not used here. The SAP 10.0 unit price is 3.76 p/kWh for home heating oil and 5.67 p/kWh for a blend of 30% used cooking oil biodiesel and 70% heating oil. The SAP 10.0 unit price for bottled and bulk LPG is 10.46 p/kWh and 6.47 p/kWh respectively. The retail price of LPG is typically less variable than heating oil, but it can vary between 47 pence per litre and 59 pence per litre (£909 - £1,141/tonne). A comparison of delivered domestic fuel prices is given in Table 2.

Table 2. Comparison of typical prices for heating fuels in the UK. Data from Energy Saving Trust and NNFCC analysis.

Fuel	Unit	Typical fuel price[a]	Average fuel price[b]	Standing charge[b]
		Pence/unit	Pence/kWh	£/year
Gas	kWh	3.7	3.74	85.53
Heating oil	Litre	53.4	5.24	-
LPG	Litre	58.5	6.86	65
Wood pellet	kg	30.0	6.45	-
Coal/solid fuel	kg	41.5	4.00	-
Electricity (off-peak economy 7)	kWh	9.1	9.10	82.25
Electricity (on-peak economy 7)	kWh	19.0	19.00	-
Electricity (Standard rate)	kWh	15.8	15.75	77.02

[a] Typical prices for heating oil and solid fuels are taken from the Retail Price Index (RPI) for April 2019. Gas and electricity from [b] and LPG and wood pellets from NNFCC analysis.

[b] Average prices per kWh of fuel energy and standing charge rates from the Energy Saving Trust for March 2019. https://www.energysavingtrust.org.uk/about-us/our-calculations [Accessed 29/05/2019]

Traditionally, residents were considered to be in fuel poverty if they spend more than 10% of household income on heating their home to a satisfactory standard. More recently, fuel poverty in England has been measured with the Low-Income High Costs (LIHC) indicator. Using the 10% definition, in total 27% of households in Scotland were in fuel poverty in 2016 compared to 23% in

Wales and 22% in Northern Ireland [17]. Data for England shows that 12.7% of households who heat their home with oil are in fuel poverty, higher than the national average of 10.7% [18]. Off-gas grid homes in some rural areas may have much higher rates - 31.5% of households in rural areas in Northern Ireland were in fuel poverty in 2016 [8]. Historically Northern Ireland has also had one of the highest fuel poverty rates in Europe, with homes spending on average 9 times more on non-gas and non-electric fuels per week than GB homes. In the 2016 Housing Condition Survey for Northern Ireland, fuel poverty levels fell dramatically from 42% to 22% owing to a combination of factors including a low heating oil price at the time [8][17]. Fuel poverty is therefore an important consideration when evaluating the potential of bioliquid heating systems, as off-grid households may not have the funds to meet the capital or operating and maintenance costs.

The total value of petroleum products purchased for heating purposes in the domestic sector was £1.105 billion in 2017, and £0.84 billion in the commercial/other services sector [2].

1.1.3 Emissions

Greenhouse gas (GHG) emissions are released during the production, supply and combustion of heating fuels. The lifecycle GHG emissions for traditional fossil fuels, as shown in Table 3, are taken from the HMT Green Book [19], which are the same as the Government emission conversion factors for greenhouse gas company reporting. Alternative GHG emission factors are also stated in table 12 of SAP 10.0 [16], although this has yet to be formally adopted.

The emission factors of air pollutants from the combustion of heating oil, LPG and gas oil in residential stationary applications are given in the National Atmospheric Emissions Inventory (NAEI). Values for GHG emissions in kg CO_2e per MWh (based on Net CV) are derived from the HMT Green Book [19].

Table 3. Emission factors for residential scale boilers burning heating oil, LPG, gas oil and coal according to the NAEI in December 2018.

Pollutant	Emission factor (g/MWh)			
	Kerosene	LPG	Gas oil	Coal
$PM_{2.5}$	6.8	4.0	6.8	1,146
NOx	183.6	170.8	183.6	448
SO_2	23.5	1.0	29.2	2,925
NMVOC	4.2	13.7	4.0	1,763
CO	205.2	87.1	205.2	17,622
CO_2e* (kg/MWh)	260	230	278	363

* Values derived from the HMT Green Book for 2017 on a net CV basis

Johnson (2012) [20] conducted a detailed comparison of emission factors for residential LPG and heating oil systems and found that lifecycle CO_2e emissions were 20% lower for LPG than heating oil. LPG systems were also found to have lower lifecycle CO_2e emissions than B20K, based on rapeseed-biodiesel. However, the carbon footprint figures underpinning this work have been revised a number of times in the years since publication.

The total annual emissions of key air pollutants and greenhouses gases for UK domestic heating fuels are presented in Table 4 for the year 2016.

Table 4. Total emissions of selected air pollutants and greenhouse gases from domestic heating fuels in 2016. Source: NAEI [21]

	$PM_{2.5}$	NMVOC	CO	NOx	SO_2	CO_2e
	Tonnes	Tonnes	Tonnes	Tonnes	Tonnes	kilotonnes
Heating oil	153	93	4,580	4,098	524	6,091
Gas oil	11	6	327	292	46	462
LPG	11	38	242	475	3	649
Solid fuel*	4264	6993	130,305	3,480	27,027	2,734
Natural gas	1,211	2,492	26,229	20,398	303	57,503

* Includes anthracite, coal, petroleum coke, solid smokeless fuel and peat but excludes wood

1.2 Bioliquid heating overview

Biomass systems have been the predominant technology receiving support from the Domestic RHI, with over 34,000 systems being installed since it was introduced in 2014. However, over the same time period around 0.4 million oil/LPG boilers and 6.2 million gas boilers have been installed, suggesting consumers are still favouring traditional gas and oil boilers, which remain relatively cheap and easy to install. Higher costs of associated works, such as fuel storage, and the additional "hassle factor" associated with switching to low-carbon heating equipment are thought to be the main reasons for low uptake relative to the total domestic heating market [22].

The familiarity of energy-dense bulk-delivered liquid fuels may be attractive to consumers and in some circumstances, bioliquids may be the most suitable low-carbon heating option for off-gas grid homeowners. There are fewer requirements for earthworks or radiator modifications than for heat pump systems, as well as lower fuel storage requirements than biomass boilers.

There are a wide range of potential feedstocks and conversion routes which may be used to supply different bioliquid products to the off-gas grid domestic heating sector. These routes are illustrated in Figure 2.

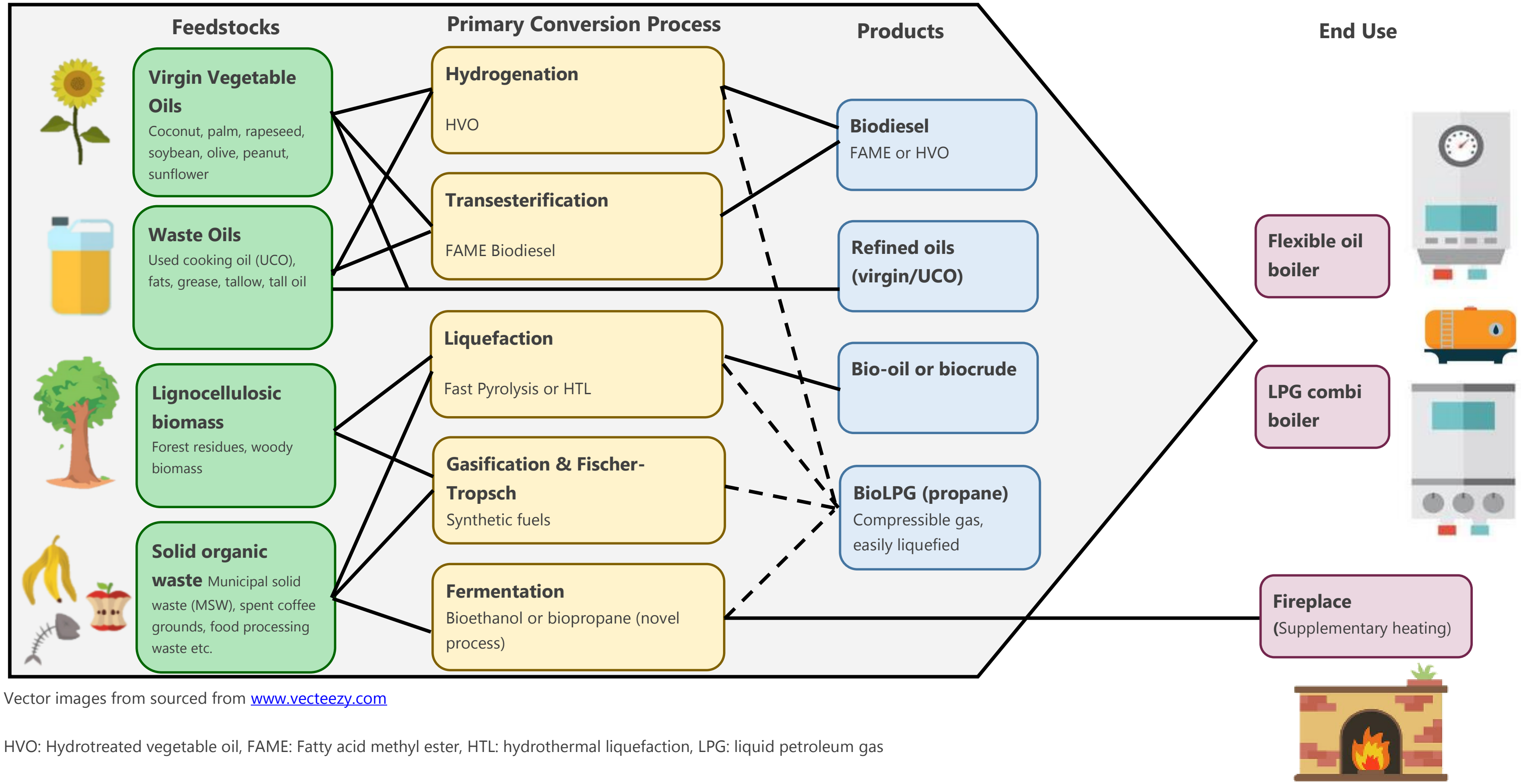
The conversion of conventional oil heating systems to use blends of biodiesel and kerosene is relatively straightforward up to 30% biodiesel inclusion (B30K). Also, LPG systems would not require any conversion or modification to use 100% BioLPG (biopropane) since the fuel is chemically identical to fossil-LPG; this is referred to as a drop-in fuel. If systems are to use blends above 30% biodiesel or to use vegetable oils or pyrolysis oil directly, converting oil-fired boilers would be more costly and complex and would mostly likely require a new dedicated boiler and storage tank. Market and technology options are discussed in depth in section 2. To date, uptake of bioliquids for heating has been limited to a handful of systems, primarily installed for trial or demonstration purposes with fewer than 20 systems thought to be operating commercially.

In October 2014 the former Department of Energy and Climate Change (DECC) published two evidence reports to support RHI reforms, on Bioliquids for Heat [5] and Biopropane for Grid Injection [23] targeting the non-domestic sector. The reports, used to assess the case for inclusion of a wider range of technologies under the RHI, reviewed the market, renewable heat potential, performance and characteristics of the respective sectors with a focus on non-domestic, grid connected consumers. The reports concluded that due to previous market failures, lack of suitable technology or concerns around feedstock availability and competition, RHI support for these technologies in the non-domestic sector was not to be introduced.

Technologically, conversion of domestic heating systems to biodiesel and BioLPG is reasonably straightforward; issues with material compatibility and burner design are well understood. Although currently none of the major domestic boiler manufacturers offer a product compatible with B100 commercially, there are no technical barriers preventing them from doing so. A more complex issue is the impact of conversion on fuel supply chains. Although readily established in other sectors, bioliquid supply chains would still require significant investment in infrastructure to enable supply and distribution to domestic customers.

The deployability of biodiesel heating systems is dependent on fuel price and fuel availability, which are currently market driven. In the longer term, policies advocating the electrification of vehicles may reduce demand for bioliquids in the road transport sector, for passenger vehicles in particular, and increase the availability for other uses, potentially making this a reasonably attractive low-cost heating fuel option for off-grid properties. However, in the shorter term, biofuel demand in the road transport sector is likely to increase due to renewable fuel mandates and its key role as a transitional fuel, whilst other renewable alternatives are not commercially available.

Solid biomass heating systems have an established mechanism supporting the use of wood chips and pellets which, although affected by competing markets such as power stations, is robust enough to weather demand and price fluctuations. There are currently limited UK sources of bioliquids that can be used for domestic heating applications, for technical, social and economic reasons. The feedstocks and supply chains are summarised in Figure 2 and discussed in more detail in section 4.



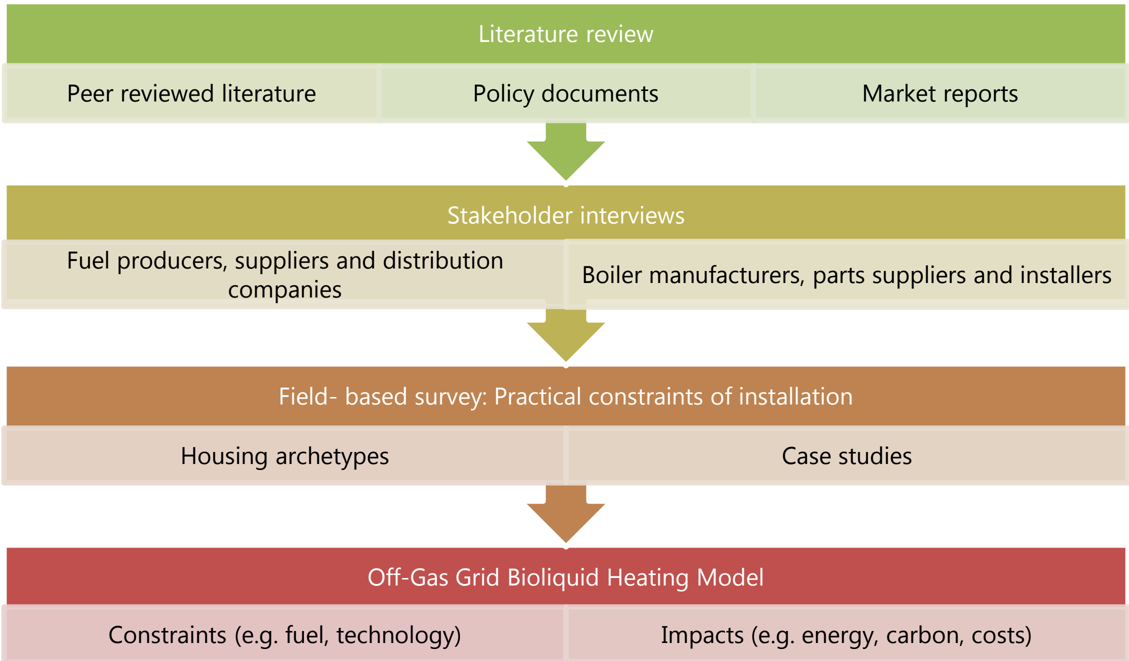
Vector images from sourced from www.vecteezy.com

HVO: Hydrotreated vegetable oil, FAME: Fatty acid methyl ester, HTL: hydrothermal liquefaction, LPG: liquid petroleum gas

Figure 2. Flow chart for the production of bioliquids for domestic heating

2 Methods

An extensive literature review was conducted in order to gather evidence on the potential of bioliquids for domestic heating, using published policy documents, market reports and peer-reviewed literature. From this, a number of assumptions were made in order to provide model inputs on fuel availability, greenhouse gas emissions and technology readiness. Findings from the literature review were supplemented and corroborated with information gleaned from key market stakeholders through structured interviews with fuel suppliers and boiler manufacturers. The stakeholder interviews provided information on technology readiness, costs & market conditions, customer receptiveness and fuel supply chains. Finally, a field-based survey of a sample of off-gas grid properties enabled the practical constraints of installation to be evaluated, including the technical requirements of conversion and any hidden costs. Data from the literature review, stakeholder interviews and field-based survey were then used to populate an off-gas grid bioliquid heating deployment model which is used to examine costs, emissions savings and fuel consumption under different scenarios.



2.1 Stakeholder interviews

Interviews were carried out by telephone, email, face-to-face and via two online surveys. This knowledge has been combined with the findings from the literature to support section 3 (Market & Technology) and 4 (Fuel Supply) of the report, as well as informing the constraints analysis encompassed within the model.

Responses were received from 15 fuel producers/suppliers, 23 boiler manufacturers/installers, 3 fuel tank manufacturers and 7 trade associations. Interview questions for fuel suppliers covered topics such as bioliquid product specifications and prices, feedstock sources and sustainability, deployability and customer receptiveness. Interview questions for boiler and equipment manufacturers covered topics such as technical requirements for burning bioliquids and blends, best practice for design and installation, feasibility of conversion, and boiler fuel flexibility, efficiency and lifetime.

In addition, in-depth discussions were held with trade associations including the Oil Firing Technical Association (OFTEC), the UK LPG Association (UKLPG), the Federation of Petroleum Suppliers (FPS) and the Tank Storage Association (TSA). These discussions were used primarily to gather information on previous trials and tests of bioliquid heating systems, and to collate knowledge on research and development in this multifaceted area. The authors also entered into dialog with commercial sector organisations to gather evidence from case studies where bioliquids have been used to heat larger non-domestic buildings.

2.2 Practical Constraints of Installation

Due to the low levels of uptake of bioliquid heating systems to date, there is an evident lack of publicly available information on the costs associated with their installation and operation. The works and costs required to install a new bioliquid heating system or modify an existing oil boiler (so it can operate on bioliquids) have therefore also been assessed by undertaking a field-based survey of a small sample of existing oil-fired properties.

In order to ensure the field-based survey encompassed three housing archetypes, the survey evaluated four properties that represented the likely range of situations and included:

- Detached property x 1
- Semi-detached property x 2
- Terraced property x 1

The survey included a detailed inspection of the existing oil-fired heating system and its components. It evaluated:

- The basic property type
- The existing fuel tank (type/location/age)
- The existing oil boiler (type/location/age)
- The works skills and expertise required to remove the existing equipment
- The estimated cost of removal
- A photo survey

The survey was augmented with the application of professional judgment concerning issues around the scope of works required and by reference to existing industry standard costs for parts, equipment and labour. This enabled the development of costs for six scenarios that will be faced by consumers considering switching to bioliquids. Results of this are presented in section 5 and Appendix C contains a full description of the findings for each property in the survey.

2.3 Deployment Model

An Excel-based Off-Gas Grid Bioliquid Heating Deployment Model was developed using industry data from a parallel study conducted by DeltaEE into the technical feasibility of electric heating in off-gas grid dwellings [24]. In order to model the suitability of the England and Wales housing stock for electric heating a number of housing archetype categories were identified, based on housing type (detached, semi-detached, terraced) and heating demand (high, low).

The functionality of the model provides a means of illustrating a range of potential deployment scenarios, the resultant heat and carbon savings such scenarios would deliver and particular constraints that may be encountered in their delivery. The model allows for the impacts and consequences of one of two growth rates to be illustrated, as shown in Figure 3.

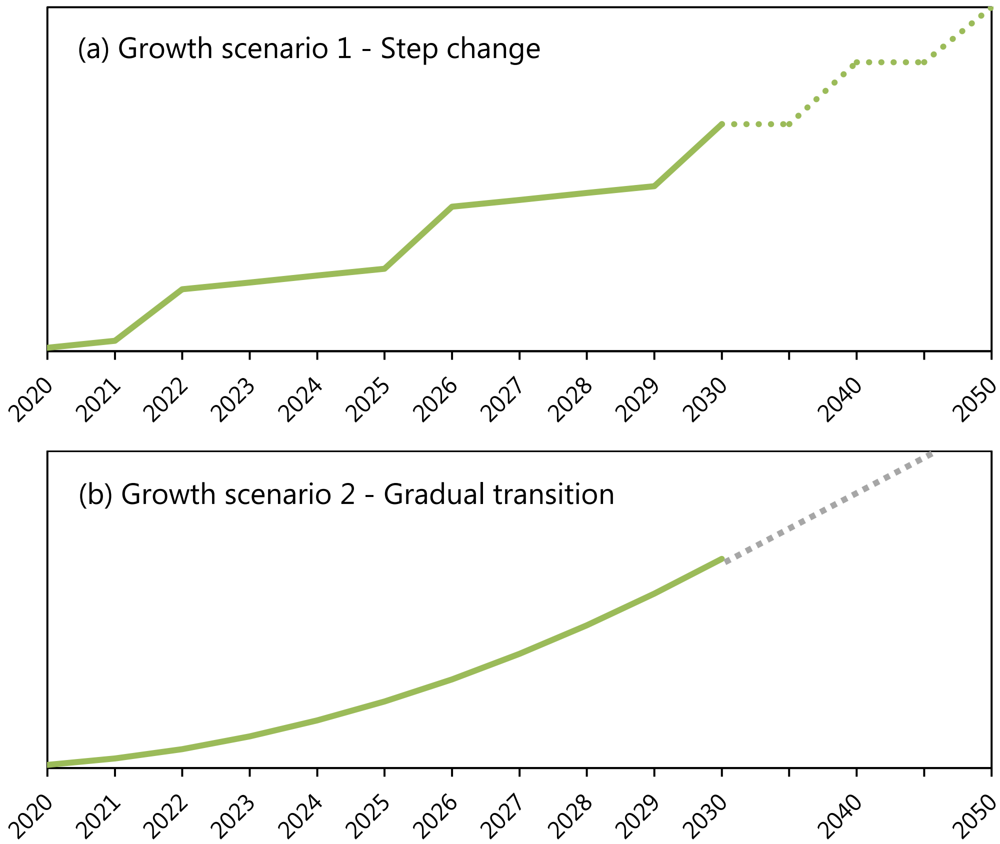


Figure 3. Growth scenarios used in the model

1) **Step change** – resulting from disruptive policies or measures being implemented at regular intervals to 2050, either on a regional or national basis; radical and often rapid changes are required in technology deployment, product availability and development of fuel supply chains. Scale of output is achieved more quickly, going beyond the natural replacement rate and contributing more significantly to the Fifth Carbon Budget[1] to 2032, with impact tailing off in the later years.

2) **Gradual transition** – market growth is more natural, driven by a clear end-point and a phased approach; allowing technologies to be deployed and skills to be developed gradually, reflecting the more natural replacement rate for oil- and LPG-fired heating systems, based on the typical lifespan of such systems. Fuel supply chains would have time to develop and adapt; supply constraints are likely to be less significant. Impact less significant in the early years, but the rate of change accelerates in later years.

[1] The Carbon Budget Order 2016 - http://www.legislation.gov.uk/uksi/2016/785/made

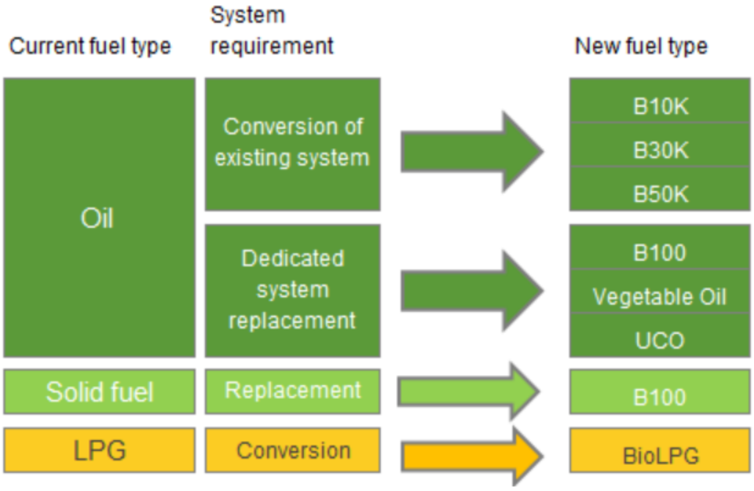


Figure 4: Illustration of technologies and fuel types covered in the deployment model.

The model illustrates delivered annual heat output for the selected deployment scenario; highlights technology or fuel supply constraints, and when these may be encountered based on current availability; delivered carbon savings, based on standard emissions values for each technology and fuel-type combination; and illustrative costs for each technology and fuel-type combination, for each housing archetype.

All data used to populate the model has been obtained from a combination of literature and stakeholder engagement. A summary of the main input values (assumptions) and key findings from the deployment model are presented in section 6.

3 Market and Technology

Due to their physical properties, unless blended with fossil-fuels, bioliquids cannot be treated as drop-in fuels to conventional oil-fired heating systems. There are two options for utilising bioliquids for heat generation:

1) **Converted heat plant** – conversion of an existing kerosene, LPG or gas-oil fired boiler to one which is instead capable of burning bioliquids.
2) **New dedicated bioliquid heat plant** – installation of a new purpose-built boiler system, specified to burn bioliquids.

Domestic-scale heating technologies capable of utilising pure biodiesel or 100% virgin and used-cooking oil have been developed, while the use of pyrolysis oil is currently under research and development. Blended fuels are also an option and can be used to varying levels in existing and new equipment. The nature of the equipment required will be determined by the demands of the consumer and the type of the existing system to be replaced. BioLPG is a drop-in fuel and can be used in existing domestic LPG boilers, as discussed in section 4.4

There are three key boiler types as shown in Figure 5. Boiler type does not necessarily correspond to housing archetypes – although combination boilers are more common in modern properties, some older properties have opted to upgrade their heating system in order to remove the need for water storage tanks. Regular/heat only boilers are used to feed a hot water storage cylinder in conjunction with a cold-water header tank which is usually in the loft. System boilers also require a hot water storage cylinder, but the boiler provides the pressure head, removing the need for the header tank. Combination boilers heat water instantaneously from the mains at higher pressure and do not require a storage or header tank.

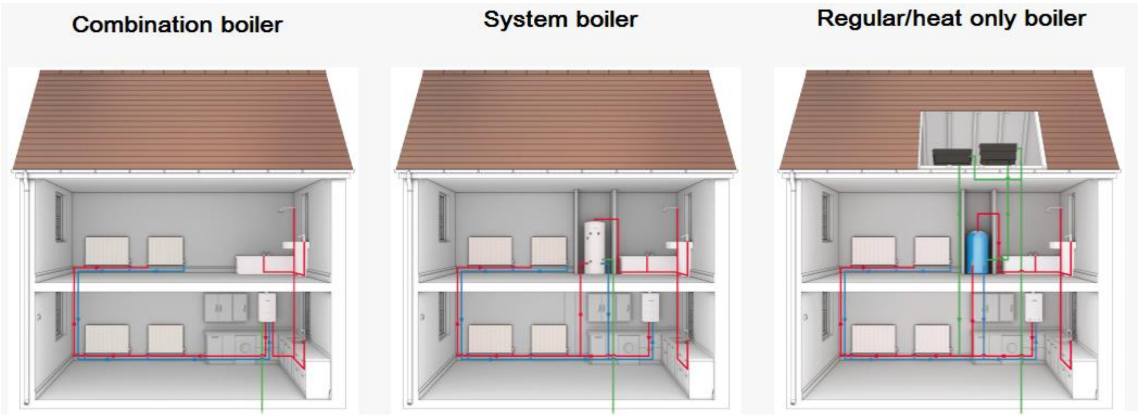


Figure 5. Key boiler types. Image source: Worcester-Bosch[2]

Additionally, boilers may be single/multi-pass or condensing which affects the efficiency of the appliance. EU Regulations 811/2013 & 812/2013 supplementing Directive 2010/30/EU came into force in September 2015 for space and water heaters, known as the Energy Related Products (ErP)

[2] Further explanation of boiler types and terminology is available at https://www.worcester-bosch.co.uk/products/boilers/explained

regulations. ErP sets minimum efficiency criteria for electric, gas and liquid heating appliances up to 400 kW and energy labelling requirements for appliances up to 70 kW. ErP efficiency labelling replaced the SEDBUK efficiency rating system which was used in the UK prior to September 2015. However, heaters using gaseous or liquid fuels derived from biomass are excluded from the ErP regulations.

From 6 April 2018, the minimum efficiency of new domestic gas boilers in England was raised to 92% ErP, through the Boiler Plus Standard. There are additional requirements to install flue gas heat recovery, weather and load compensation, and smart controls. Higher efficiency standards were also considered for oil boilers, but alternative low carbon technologies were favoured to support Government targets to phase out the use of high carbon off-gas grid fuels during the 2020s.

Fuel types, availability and compatibility are discussed in more detail in the subsequent sections.

3.1 Conversion of existing oil boilers

In order to minimise the costs of switching to bioliquid heat, conversion of an existing boiler rather than investment in a new heat plant may provide an attractive option. Some capital outlay is likely to be required for replacement parts, and this approach will only be suitable where the existing boiler is in reasonable condition and likely to continue operating efficiently for long enough to achieve a reasonable return on investment [25].

There has been some previous research investigating the viability of using blends of heating oil (kerosene) with biodiesel, in existing residential kerosene boilers. An unpublished bioliquid fuel project, undertaken by the Oil Firing Technical Association (OFTEC) and its members, involved extensive research and trials carried out at various domestic and commercial sites, all of which were closely monitored over a 12-month period. These trials revealed that in order for bioliquid blends to be used successfully, some conversion of the boiler and ancillary kit is necessary.

A number of different bioliquid blends were tested, with B30K (30% Biodiesel and 70% Kerosene) chosen to be the most favourable blend used amongst domestic oil users, mainly due to the balance between the biodiesel concentration in the blend, the ease of conversion of the existing boiler system, and the overall efficiencies. A B50K blend (50% Biodiesel and 50% Kerosene) was also tested but caused more technical issues and delivered less consistent performance, resulting in higher costs.

3.1.1 Conversion requirements

When converting a boiler to run on bioliquids consideration needs to be given to the type of bioliquid used and specifically whether a 100% bioliquid fuel or a renewable/fossil blend will be most suitable. When converting a fossil boiler, the following aspects for consideration have been highlighted:

- Suitability of the boiler and the likely operational life remaining
- Burner design and ability to combust the chosen bioliquid/blend efficiently
- Burner size and whether this is matched to current heat demand
- Fuel storage and compatibility of plant components with bioliquids
- Maintenance requirements of the converted system and whether there is suitable access

Conversion is relatively straightforward, requiring simple replacement of component parts which can be sourced easily and installed by a standard trained heating engineer or qualified plumber. Before considering conversion, the age and condition of the existing boiler should be assessed to ensure the additional investment in replacement parts and labour can be justified and the system will continue to operate for long enough to pay back the investment. Following discussions with industry, conversion kits and installation is estimated to cost around £500-£1,000 per system. Although a range of up to £1,500 has been stated in discussions with some installers, this has not been substantiated with suitable evidence. The high end of the range is expected to reflect an ageing system which requires full replacement of the burner, filters, seals, tank and some ancillary pipework, although in these situations it is likely a new boiler would be more cost-efficient in the long term.

Manufacturers have been working on improving the versatility of their systems and components since bioliquids were first considered, before the Domestic-RHI was introduced in 2014. Seemingly, most systems installed or replaced within the past 5 years should be compatible with a blend of up to 10%, and in some cases 30% biodiesel, depending on the choice of burner. For example, Riello burners are suitable for blends up to B30K, but higher blends may affect the pump, valve block and flexible oil lines and are therefore not covered under warranty[3]. Other brands of fuel flexible burners are available, as discussed below.

Most manufacturers now give specific instructions for the use of biodiesel blends in the product manual. Examples of B30K compatible boilers include the Grant Vortex Eco condensing boilers, which have been compatible since May 2011. Many manufacturers adopted a fuel flexible approach to new products following the initial research into bioliquids over ten years ago, as well as the field trials conducted at Reepham, Norfolk in 2010/2012. These trials were spearheaded by OFTEC and demonstrated that UCO-biodiesel could be blended with kerosene and burned successfully at blends up to 30%, above which more major modifications are required.

Burners

When converting a kerosene boiler to utilise a low bioliquid blend (e.g. 10-30% biodiesel), it may be possible to utilise the existing burner rather than retrofit a new one. There are five key manufacturers of burners which are incorporated into domestic boilers, including Riello, EOGB and Enertech (Nu Way/Bentone).

Pressure jet burners can be converted with relative ease and conversion kits[4] are available to assist with the replacement of oil carrying components [26]. Typically, pressure jet conversion would require at least the replacement of the atomising nozzles, fuel pumps, flexible oil lines, filters and/or filter seals [27]. However, an engineer is needed to assess the boiler to determine whether or not conversion is possible, mainly based on the condition of the existing equipment. If the conversion is not a viable option, it may be necessary to obtain a dedicated bioliquid burner [25], for which a small number of suppliers currently exist.

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[3] Further instructions for the use of blends in kerosene burners are available in the manufacturer manuals available here https://www.rielloburners.co.uk/images/content/downloads/RDB1-2_2902489-18.pdf

[4] A collection of parts needed to convert the boiler.

According to OFTEC, existing kerosene vaporising burners, such as those found in continually burning cookers and stoves, are not suitable for conversion. Bioliquid/kerosene blends should not be introduced to vaporising burners, as it has been proven that bioliquids in kerosene can immediately adversely affect vaporising burner combustion even within hours [27].

Boiler efficiency analysis, conducted by OFTEC, revealed that when an appliance is operating under full load, the use of B30K results in an efficiency loss of 0.5% when compared with kerosene, while under 30%-part load conditions, boiler efficiency increases by 1.2%. It is noteworthy that a boiler typically operates under part load for the majority of its life cycle [26].

Storage and supply systems

Findings from the heating oil project conducted by OFTEC, have shown that, subject to the use of bioliquid compatible filters and fire valves, no other modifications are required to the ancillary equipment to facilitate the safe storage and supply of bioliquid blends up to 30% (B30K) [27].

Nevertheless, all components in contact with oil must be proved compatible with bioliquids. Many common rubbers, plastics and surface coatings will degrade from contact with biodiesel and should be replaced with compatible ones when using bioliquid in pure form or as a blend [25]. Suitable materials are carbon steel and austenitic stainless steel. In addition, Teflon™, Viton® and Nylon have very little reaction to biodiesel and are amongst the materials that can be used to update incompatible equipment [28]. See section 3.6 for more detail on storage and handling requirements.

In addition, if bioliquids are to be put into an existing oil tank, enquiries should be made with the tank manufacturer to ensure that the tank material is compatible to store the desired fuel. Tanks should be assessed for their general condition and cleaned to remove all water, sludge and debris[5] before introducing bioliquids. However, it should be noted that cleaning an existing tank sufficiently can be extremely difficult, and in vast majority of cases investment in a new tank will be preferable [25].

Maintenance

Maintenance of a converted system would be carried out by standard engineers and running costs (excl. fuel costs) and service/maintenance requirements should be the same as for a conventional oil-fired heating system. Regular servicing would be paramount, to ensure efficient operation and to monitor the condition of the system, considering that specific components may have been modified as opposed to purposely installed to operate on bioliquid fuels. Some of these issues may be overcome through a service agreement contract or boiler breakdown cover, discussed in more detail in section 6.4. Fuel costs are discussed in section 4.

[5] Biodiesel (FAME) is hygroscopic and therefore, it absorbs water and can promote bacterial growth. It also acts as a cleaning agent and will pick up any debris and contaminants contained within an oil storage tank and carry it downstream causing filter blockages [27].

3.1.2 Market

Until 2016, the UK was the largest market for domestic gas boilers in the world with an estimated value £2.5-3.0 billion [29]. With an established knowledge base and supply chain, UK boiler manufacturers are well equipped for technical innovation.

Even though conversion of existing boilers is possible from a technical perspective, at the time of writing there is no market for kerosene-biodiesel blends to be used in domestic heating applications. Firstly, it is not commercially attractive for householders to convert their kerosene boilers to handle bioliquid blends and secondly, there are no fuel distributors who supply bioliquid blends to the domestic market, so awareness and infrastructure need to be addressed before uptake increases. Despite this, feedback from industry has shown that new kerosene boilers on the market today are able to be used with either B10K or B30K, with minor adaptations, depending on the manufacturer's choice of burner.

3.2 100% biodiesel boilers

The design of 100% biodiesel boilers is relatively straightforward, with many options the same as those that apply on a standard oil boiler, e.g. single (reverse) flame, multi-pass, and/or the condensing design.

A key difference between the design of kerosene and dedicated 100% biodiesel boilers is in the burner, which can be optimally designed to burn 100% biodiesel (B100) from the outset. There are also boilers with dual fuel capability, which consist of a single burner with two fuel inputs, enabling the user to switch from one fuel to another based on the most economical option each time [25]. However, dual fuel systems may not be economical at the small scale due to the additional infrastructure requirements for fuel storage and handling.

Amendments to the storage and supply systems must be made if the boiler is a replacement in an existing system, or new systems would need to be specified accordingly. The inclusion of a preheated fuel tank[6], to lower the viscosity of B100, is a prerequisite to ensure proper atomisation and thus effective combustion. The tank size and location would also need to be considered, and it must be insulated to ensure that the contents remain above -5°C at all times. Common materials used in oil boilers may degrade when in contact with biodiesel and therefore guidance must be followed on material compatibility, such as that provided by Concawe report 09/09 [30]. Suitable materials are carbon steel and austenitic stainless steel while copper, brass, bronze, and rubber are unsuitable for storage and supply equipment (e.g. storage tank, pipes, pumps etc.). Finally, there must be sufficient pressure control of B100 at the storage tank and in the pumped feed distribution. Pipe sizing must be large enough to maintain a low pump suction head and must prevent overpressure at the burner oil pump inlet [31].

The cost of solid biomass heating systems is often prohibitively high due to the additional infrastructure required to receive, store, transfer and burn solid fuels. Bioliquid boilers use a more

[6] B100 must be maintained in storage and in circulating pipework at a minimum temperature of 5˚C and generally in the range 5˚C to 15˚C.

energy dense fuel and therefore require a smaller storage area, so costs are lower. Nevertheless, costs remain higher than for conventional fossil-oil boilers, simply due to economies of scale and the lack of products currently available on the market, as well as a lack of suitably trained installers and heating engineers. The average cost of solid biomass heating systems is reported to be between £440 and £880 per kW [6]; whilst conventional fossil-oil heating systems typically cost between £90 and £120 per kW; and biodiesel boilers cost in the region of £150 - £230 per kW, based on discussions with existing suppliers and installers.

There are several case studies of B100 biodiesel used for commercial scale heating and larger residential developments. For example, the PwC office buildings at More London and One Embankment Place use a biodiesel produced from locally sourced used cooking oil in a trigeneration plant[7] and the 16-flat Pitfield Street development also in London uses a Hamworthy B100 biodiesel boiler[8]. In addition, fuel suppliers such as Crown Oil, Nationwide Fuels and Cooke Fuels offer a 'CHP biofuel' specifically for this market, although demand is currently low.

3.2.1 Market

Even though from a technological perspective 100% biodiesel boilers are available, the market is limited, mainly due to their relatively high cost, the absence of support and the higher price of B100 fuel compared to fossil alternatives. Thus, there are a few manufacturers who supply this type of boiler at the present. Table 5 lists the manufacturers and suppliers identified along with a brief description of the available products.

Table 5: Dedicated biodiesel boilers available on the market

Manufacturer & Product	Short Description	Information Source
Atlantic Boilers **R Series Condensing B100 Biofuel Boiler**	Condensing boiler which comprises two distinct heat exchangers and a pre-heating fuel tank. Boiler efficiency: exceeds 92% GCV throughout the heating season.	https://www.buildingservicesindex.co.uk/entry/34307/Atlantic-Boilers/B100-BioFuel-R-Series-condensing-boiler/
Hamworthy **B100 Biodiesel Ensbury LT**	Ensbury pressure jet boilers are designed with a three-pass heat exchanger and are manufactured from high quality steel. Suitable for dual fuel arrangements (mainly Biodiesel and kerosene). Boiler Efficiency: up to 95%	https://www.hamworthy-heating.com/Products/Commercial-boilers/Ensbury-pressure-jet-boiler

Each of the suppliers listed above offers full design and installation, along with user manuals and service/maintenance guides to accompany their products. It is likely manufacturers' warranties would

[7] More detail available at https://www.cibsejournal.com/general/food-for-thought-power-by-cooking-oil/

[8] More detail available at https://www.hamworthy-heating.com/About-us/Case-studies/Residential-boilers/Pitfield-Street-London

not be valid if installation was not carried out by a suitably trained engineer. However, at present no installation standards or best practice guides exist, so determining what deems an installer “suitably qualified” is difficult.

3.3 Virgin and used-cooking oil boilers

Heating oil, biodiesel, vegetable oils and used cooking oils (UCO) have their own specific behaviour that distinguishes one from another and this is related to their specific physical and chemical nature. The fatty acid composition, high viscosity and high volatility are key differences in the behaviour of vegetable and used-cooking oils in boiler systems, compared to other fuels [32]. As a result, these oils are more difficult to handle, and their efficient combustion would require a slightly different boiler design optimisation (e.g. burner, fuel storage) than in the case of biodiesel.

As with biodiesel, accurate temperature control of oils is essential to avoid swings in viscosity which result in combustion variation. Oil pre-heating is therefore one of the key design features, to achieve full atomisation[9] along with suitable tank siting and insulation to protect stored fuel from extreme temperature conditions occasionally experienced in the UK.

When it comes to fuel handling, vegetable and used cooking oils must be filtered to remove impurities before entering the burner. There is evidence that these types of oils can block the nozzle due to the presence of residual oil seed husks and particles, which are not visible in liquid form to the naked eye. In addition, vegetable oils differ in thickness depending on their plant source, while their processing also affects the end-fuel properties, as used vegetable oils can vary considerably in contamination levels and quality[10] [33]. Therefore, considering the inconsistent quality and the requirement for filtration, to ensure an efficient and consistent combustion, a domestic fuel supply chain would require quality assurance steps to improve the properties and reliability of the end fuels [25].

Boilers burning waste oil (used cooking oil, waste motor oil, lubricating oil etc.) are not suitable for installation in a domestic property as the pre-heating of the oil can sometimes create an odour and thus, they should be sited in a separate building (e.g. boiler house or garage), and the warm water would then be transferred via insulated pipes into the property [34].

Virgin and waste-oil boilers typically achieve lower efficiencies than biodiesel boilers, requiring greater attention in terms of service and maintenance (filter changes, cleaning, etc.) and incur greater running costs for routine maintenance and replacement parts. Little evidence is available to substantiate these claims made by installers as there are few products available in the UK and no installers with direct experience of commercial UK installations.

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[9] That applies in pressure jet burners. Rotary cup burners can handle bioliquids with high viscosity. However, their high cost and the fact that daily maintenance and monitoring is required for reliable operation [143], can make them impractical for residential use.

[10] Biodiesel is a more refined fuel and it is better for boilers as it is smoother and has a lower viscosity than virgin and waste-cooking oils [144].

3.3.1 Market

Currently, adequate quality vegetable oils are not commercially available to domestic users, and thus the market for dedicated virgin- and waste-oil boilers is limited. The development of a fuel supply chain, including quality assurance steps to improve and monitor the quality and properties of vegetable oils, could result in wider adoption of this type of boiler. However, concerns regarding alternative uses of virgin oils for food, as well as high feedstock prices due to high demand and competition for other industrial uses, might be factors that will prevent the growth of that market in the future. These issues are discussed in more detail in section 4.1

Straight vegetable oil use in transport has been proven to be technically possible but there are a number of barriers limiting the widespread use of the fuel; including fuel viscosity, deposit build-up and shorter engine lifetime[11]. SVO is also used in a small number of stationary applications including for back-up power generation and combined heat and power (CHP) plants but the number of these installations is far outweighed by those using biodiesel produced from vegetable oil or used cooking oil. It is possible to blend vegetable oils with fossil fuels for boiler applications; although a number of studies have considered this, no field trials have been undertaken, as has been the case for biodiesel.

In the case of used cooking oils, households do not produce enough used cooking oils to ensure sufficient fuel supply for their own demand for heating. In addition, despite commercial collections of used cooking oil being increasingly prominent there are no supply chains to support delivery back to domestic premises. More detail on the UCO supply chains is given in section 4.2.1.

Currently, biodiesel, the major alternative outlet for used cooking oils, has greater demand and stronger market pull due to the availability and nature of support through the Renewable Transport Fuels Obligation (RTFO). However, if demand were to increase and the heating sector become more competitive, as in the case of vegetable oils, there are no technical constraints that could not be overcome through further research and boiler design optimisation. Several manufacturers now offer products capable of burning waste and virgin oils, but they are generally bespoke systems for certain applications and costs remain prohibitively high. Table 6 lists the suppliers of dedicated vegetable and waste oil boiler systems identified.

Table 6: Dedicated vegetable and waste oil boilers available on the market.

Supplier & Product	Short Description	Information Source
Z.M Heaters **Termomont DTTK series of waste oil boilers**	Run on waste engine oils, hydraulic oil, vegetable oils, bio-diesel and a range of other fuels. Outputs from 20 to 1200kW. * Includes basic wire mesh filters to protect the heaters' mechanical parts from larger debris/particles.	http://www.zmosystems.co.uk/waste-oil-boilers.php

[11] For more information on the use of vegetable oils in engines, see https://www.nrel.gov/docs/fy14osti/54762.pdf

FLEXIHEAT UK Ltd **Waste/Multi-oil Boiler**	Steel boiler compatible with pressure jet oil burners. Run on vegetable oils, used cooking oils, biodiesel, hydraulic oil and a range of other fuels. Outputs from 12 to 1200 kW. * Oils are preheated before entering the burner. ** For waste vegetable oil, the fats have to be removed via settling out, and the oil should also be filtered down to 5 micron.	http://www.flexiheatuk.com/wp-content/uploads/2016/06/FMOB-Multi-Oil-Boiler-Brochure-11.07.2017-1-1.pdf
Clean Burn **Waste Oil Boilers**	Boilers run on waste oils. Outputs range from 41 to 146 kW. The Company also offers fuel collection, supply & distribution and the Clean Burn Recycling Center; the ideal system for collecting, storing and generating heat recovered from waste oils. * US based with International distribution. ** Targeted at commercial and industrial sectors but scale may be appropriate for large domestic properties.	https://www.cleanburn.com/clean-burn-products/waste-oil-boilers/
EnergyLogic **Waste oil boilers**	Boilers run on waste oils. Outputs range from 50 to 150 kW. * US based with International distribution. ** Targeted at agriculture, commercial and education sectors but scale may be appropriate for large domestic properties.	https://www.energylogic.com/waste-oil-boilers/#model

Most of the suppliers listed above offer full design and installation packages, along with appropriate technical manuals and service/maintenance guides to accompany their products. Manufacturers' warranties would not be valid if installation was not carried out by a suitably trained engineer. However, at present no installation standards of best practice guides exist, so determining what deems an installer "suitably qualified" is difficult.

3.4 BioLPG boilers

Bio-LPG (Biopropane) is a drop-in fuel and can be used in existing LPG boilers and appliances without affecting their performance and efficiencies. This means that for existing LPG users, no capital expenditure is required to switch from fossil LPG to bioLPG in their boilers. Thus, the deployment of bioLPG entirely depends on fuel availability and the development of an efficient supply chain, rather than on the boiler technology. The majority of domestic gas boiler manufacturers also offer dedicated LPG boilers, or they can be converted to LPG with a simple conversion kit costing £50-£100.

3.4.1 Market

Currently around 193,000 British homes are using LPG boilers to heat their homes [35]. However, Calor is currently the only energy company who supplies bioLPG to off-gas grid homes and businesses across the UK, representing the first large scale bioLPG distribution around the world. Calor has recently signed a commercial agreement with Neste, the only producer of bioLPG worldwide, to purchase 40,000 tonnes of bioLPG every year and this is enough to provide fully renewable heat to an equivalent of 30,000 homes[12]. BioLPG is available to home energy customers, who can opt for a 40% renewable Green Energy Plan[13], which means that 40% of the LPG received is from renewable sources whilst 60% still comes from fossil sources. Other major LPG suppliers such as Flogas, Avantigas and some local firms are also investing in research and development for renewable alternatives to fossil LPG. Further information on the fuel supply chain is discussed in section 4.4 .

3.5 Pyrolysis oil boilers

At present, there are no residential heating systems capable of utilising pyrolysis oil in the UK market. Preliminary work done in the USA has suggested that raw bio-oil combustion is not feasible in domestic scale boilers due to the "*oil's high viscosity, corrosivity, high water content, and tendency to polymerize to form residues on burner components*" [36]. However, a Horizon 2020 project, ''Residue2Heat'', is in progress, and one of its primary objectives is to develop an efficient small-scale fast-pyrolysis bio-oil (FPBO) residential heating boiler (20 – 200 kW_{th}). There are a number of technical challenges to be overcome in order to facilitate the use of FPBO in residential boilers. The approach of the ''Residue2Heat'' project is holistic, and its overall ambition is to address all technical and non-technical challenges associated with the use of residual biomass for sustainable residential heating.

According to Hermanns and Feldhoff (2016) [37], the first challenge is to produce pyrolysis oil with a consistently high quality and highly standardised physical-chemical properties, despite the wide range of possible raw materials. The second challenge refers to the fundamental aspects of bio-oil combustion, since its properties differ from those of conventional fuels, and in order to control and improve a burner system, a better understanding of pyrolysis oil combustion and spray parameters is essential. Finally, the third challenge is the technical adaptation of a highly efficient condensing heating system for the use of FPBO.

The fuel properties of FPBO are discussed in chapter 4.5 Due to high corrosivity and low pH, all piping, tubing, seals and boiler ancillary equipment in contact with FPBO must be corrosion resistant. Recommended materials include polytetrafluoroethylene, high density polyethylene, polyvinylchloride, polypropylene and grade 304 or grade 316 stainless steel [38]. Whilst there are no known examples of FPBO use in residential boilers, several industrial installations (>1 MW_{th}) exist which burn FPBO in accordance with BS EN 16900 in Europe and ASTM D7544 in the USA. Among the most established examples is a 180 MW CHP district heating plant converted to pyrolysis oil by Fortum Otso in Joensuu, Finland,in 2013. More recently, a 29 MW_{th} dual fuel steam boiler was installed at the dairy firm FrieslandCampina in Borculo, Netherlands, using BTG-BTL fuel. The boiler burns approximately 3 tonnes of FPBO per hour and uses natural gas for start-up and as a back-up fuel. In the USA, a 7 MW_{th} dual fuel boiler was installed at Bates College, Lewiston, Maine, in a collaboration between Ensyn Fuels and Envergent Technologies. It was found that the boiler emitted less NOx and SO_2 compared with grade 2 fuel oil but had similar PM emissions. Lifecycle GHG emissions were found to be around 10 g CO_2e per MJ, approximately 87% lower than fuel oil[14]. Similar results were obtained

[12] Neste, https://www.neste.com/neste-delivers-first-batch-100-renewable-propane-european-market
[13] Calor, 40% renewable Green Energy Plan - https://www.calor.co.uk/quote-tool
[14] Further information is available at https://www.bates.edu/news/2019/01/17/campus-construction-update-jan-18-2019/

from a 30 MW district heating scheme in Youngstown, Ohio, USA, by replacing natural gas with pyrolysis oil.

The development of a residential scale burner through ''Residue2Heat'' will start with MEKU, a commercially available liquid fuel burner, which will be adapted to burn FPBO. Commercial guarantees are now available on flexible burners available from Stork Thermeq (Netherlands) and Dreizler (Germany) for using FBPO, and dedicated burner manufacturers include Oilon Oy, Finland.

The ''Residue2Heat'' project is expected to complete in late 2019 at which point it is expected there will be a robust fast-pyrolysis bio-oil boiler available for commercialisation. However, at present no detail is available on the costs or performance of such products in the domestic heating market.

3.6 Bioliquid storage and handling

In order to facilitate the use of bioliquids and blends in the residential heating sector, significant investments are required in upstream infrastructure. This is particularly the case for vegetable oils, UCO, biodiesel and blends such as B30K, whereas BioLPG is a drop-in fuel and would not require separate storage or blending facilities.

Industry feedback has suggested that blending would need to be carried out at terminals, before transport to distribution yards as to blend at the distribution hub would be prohibitively expensive. This presents a commercial opportunity as there are currently no companies offering blended kerosene commercially. Fuel importers and terminal operators would need to invest in additional tanks and racks for the storage of biodiesel, kerosene and for the blended fuel (B30K, B50K etc). At the present time there is very limited capacity in the >300 terminals in the UK and therefore the number of blend options would need to be kept to a minimum. Shareholders also require short to medium term market certainty for capital investment in new tanks and ancillary equipment such as pumps, filters, seals and blending equipment. Guidelines on the material compatibility and requirements for terminal storage and blending of FAME biodiesel is given in Concawe (2009) [30].

The off-gas grid market presents unique distribution challenges due to the rurality of the consumer base. Larger transport distances and more infrequent deliveries can lead to higher costs. Furthermore, challenges around compatibility of existing distribution vehicles, and the investment required to increase distribution capacity to accommodate a greater range of fuels for domestic supply require consideration.

<u>Heating oil tanks</u>

Kerosene storage tanks are typically fabricated from plastic (OFS T100) or steel (OFS T200) and are installed in a variety of locations around a property, including inside and underground. At the household level, the provisions for the siting of fuel storage tanks are given in the Building Regulations 2010 incorporating 2013 amendments Document J, provisions J6 and J7.

Most commonly tanks up to 3,500 litres are sited externally aboveground in a suitable location at least 1.8 m from the property, in accordance with Building Regulations Document J. The key types of tank are single skinned, double-skinned and integrally bunded. The majority of older domestic tanks are single skinned, whereas most commercial tanks are underground integrally bunded, whereby a protective containment (bund) is built around the inner tank which can hold up to 110% of the contents to ensure spills or leaks can be safely contained. A co-benefit of the protective bund is that it creates a microclimate around the fuel, partially preventing condensation and cold weather problems. A typical integrally bunded B100 tank is shown in Figure 6.

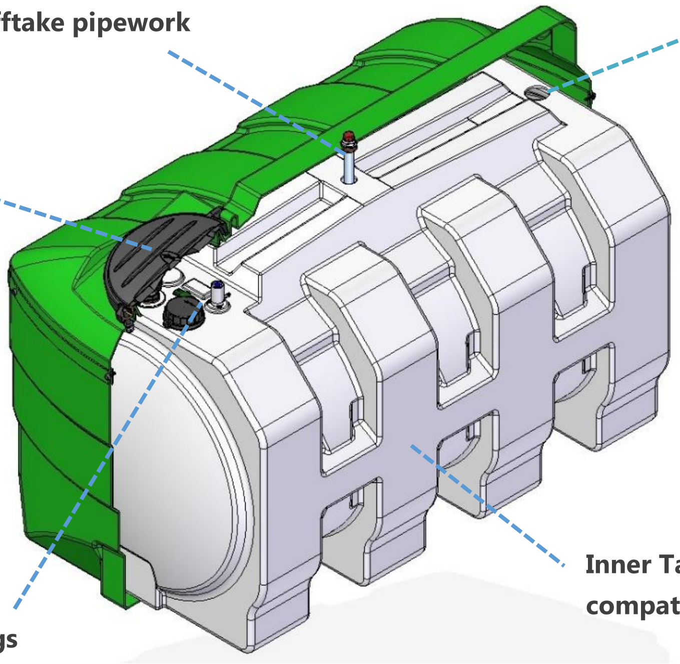


Figure 6. An example of a B100 storage tank, the BioBund from Harlequin

The inner bund of B100 tanks should be lined with high resistance materials such as Teflon™, Viton® and Nylon. Industry feedback has suggested that standard domestic oil tanks are currently capable of storing a 10% blend, and possibly up to B30K without major modifications. However, due to the cleaning effect of biodiesel, tanks must be thoroughly purged before any blended fuel is added in order to remove any sludge, sediment and water build-up. Higher blends may require a new dedicated B100 tank or to clean and re-line the existing integrally bunded tank with high grade polymers, costing approximately 15% of the price of a new tank.

Unlike LPG tanks, most households using oil are in direct ownership of the fuel tank. Fuel deliveries are typically annually or biannually, and the lifespan of the tank is approximately 20 years, though failures may occur from 15 years onwards. It is not uncommon for the tank and boiler to be replaced at different times, so the age of these major system components may not necessarily be aligned. Typical domestic tanks have a capacity of 1000-2500 litres and the vast majority of new tanks are integrally bunded. The installed cost of a new tank varies from £1000-£2000 depending on site requirements and industry advice is that new B100 tanks should be approximately half the size of heating oil tanks, in order to increase fuel turnover.

LPG

LPG tanks are typically constructed from welded steel and hold contents under medium pressure (0.0075-2.0 bar). Typical tank capacities are 1500-2500 litres and there must be a minimum of 3-metre separation distance from buildings and boundaries. There are a range of siting options including underground and aboveground on a concrete base [39]. Suppliers usually take ownership of the tank and maintenance for a fixed amount, paid by the customer as a standing charge at a typical rate of 17-18 pence per day. The equipment may be transferred between suppliers, as shown in Figure 7.

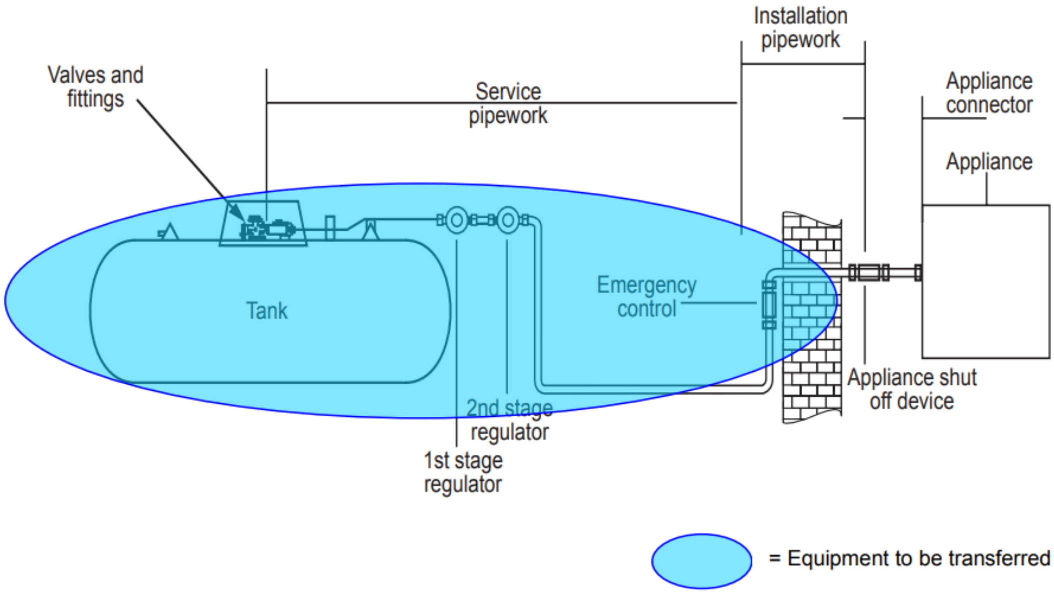


Figure 7. Typical domestic LPG installation showing equipment owned by the supplier [13]

A 2006 market investigation into the supply of domestic bulk LPG found that the rate of switching between suppliers was very low, leading to overpayments by many customers [13]. As a result, a number of orders have been implemented to increase competition in the domestic market, including simplified tank transfer. The *Domestic Bulk LPG Tank Transfer Price Calculator*[15] was launched as an online tool to help consumers better understand the associated costs.

[15] The calculator is regularly updated and available online at https://www.gov.uk/government/publications/liquefied-petroleum-gas-lpg-market-orders-and-calculator

4 Prioritised fuels and supply chains

The deployment potential for each of the technologies described in the previous sections, is highly dependent on the availability and economically viable supply of the relevant fuels. At the present time the availability of bioliquids to the domestic heating market is very limited. Whilst BioLPG is commercially available and several heating oil suppliers also offer a bioliquid or 'CHP biofuel' product, in reality these products are not yet available to the domestic consumers. The following section summarises and evaluates literature available on these fuels to determine:

- what is their availability for future uses,
- where the end-use fuels are produced and in what quantities,
- what and where the competing markets are,
- what the production costs are and what are factors affect their economical supply,
- and finally, how these fuels can be supplied to consumers.

The following end-use fuels are considered those currently or most likely to be used in domestic heating systems, and which are compatible with the technologies identified at section 3:

- Vegetable oils
- Used Cooking Oil (UCO)
- Biodiesel (FAME)
- BioLPG (Biopropane)
- Pyrolysis oil

Other feedstocks have been dismissed due to their lack of availability compatibility or other concerns, as described below, around their use in the domestic sector.

Firstly, **tallow**, an animal fat obtained by rendering animal carcases and waste from the food industry, is deemed unsuitable as it needs to be disposed of in WID-compliant combustion systems, which is inappropriate at domestic scale. Currently almost half of the tallow produced in the UK is used to supply heat to the rendering process itself, therefore availability is limited, and little growth is expected in future years.

Secondly, **tall oil**, also referred to as liquid rosin or tallol, is a viscous yellow-black liquid obtained as a co-product of the process of pulp and paper manufacturing, principally in Scandinavia and North America. Tall oil is difficult to handle and requires further processing ("de-gumming", to remove wood particulate contaminants) if to be used in engines designed for diesel fuel. Tall oil can be blended with other bioliquids to produce a lighter bioliquid which has similar properties to Light Fuel Oil, making it more suitable for electricity generation via dedicated CHP units or for co-firing in larger oil-fired power stations. Due to its composition it is deemed unsuitable for combustion in small-scale domestic boilers.

It should be noted, the Contracts for Difference (CfD) support mechanism has been available to large scale renewable energy generators in the UK since 2014 and was adopted by the Government as part of the Electricity Market Reform (EMR). Eligible technologies are currently grouped into one of three technology 'pots' which compete for contracts during allocation rounds, with bioliquids falling into the budget for Pot 2 comprising "less established technologies". Technologies using solid and gaseous biomass feedstocks are required to meet sustainability criteria to be eligible for support under the CfD scheme. The *Bioliquid Relevant Percentage* sets the greenhouse gas emission savings that bioliquids must achieve for the generation to be eligible for support and count towards the UK's emission savings under the Renewable Energy Directive[16]. These levels vary depending on when generating stations using bioliquids started operation. As waste-fuels are favoured under this scheme, competition for bioliquids from the renewable power sector may increase in future years. The fuels deemed suitable, now or in the future, for domestic scale combustion are described and discussed in more detail below. Typical annual oil demand for a domestic property ranges from 600 to 3000 litres, dependent on property type, age, location, occupancy and EPC rating. In 2017, kerosene consumption in the residential sector was 1.9 million tonnes (2.4 billion litres) [2].

4.1 Vegetable Oils

4.1.1 Arisings and availability

In 2017, the UK produced 0.849 million tonnes of vegetable oils (84% rapeseed) [40]. Exports were 0.191 million tonnes (40% rapeseed) and imports were 1.131 million tonnes (37% palm, 30% sunflower). The total current availability is therefore estimated at 1.98 million tonnes or 2,176 million litres per annum.

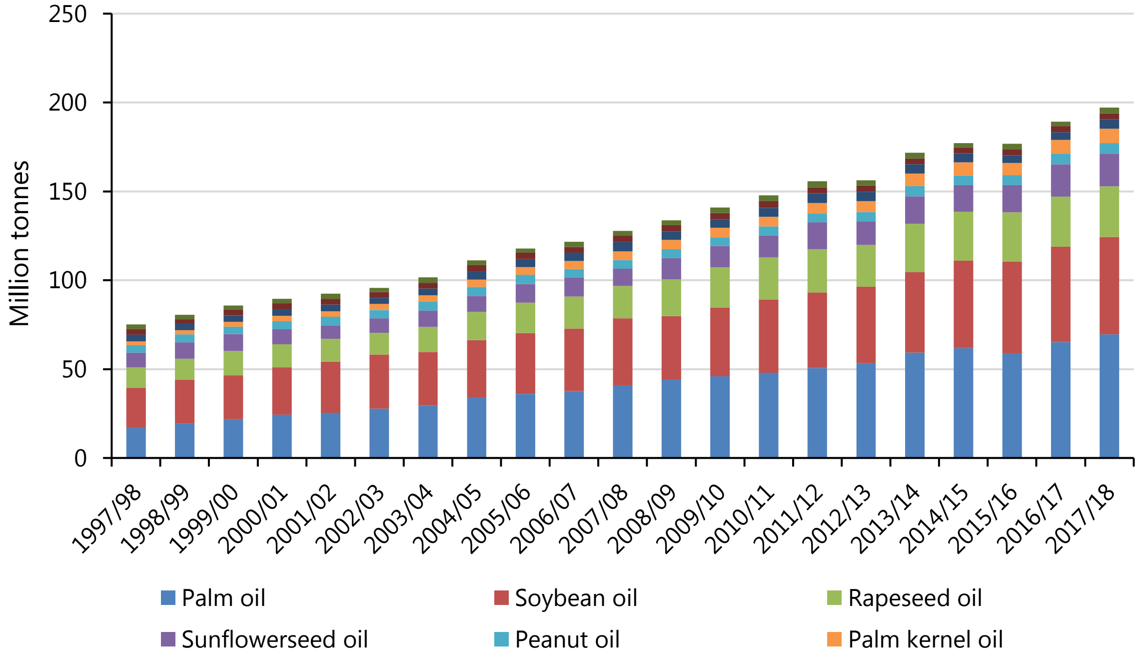


Figure 8: Worldwide production of vegetable oils. Source: USDA

16 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/736588/Part_B_Consultation_Response.pdf

Worldwide, the consumption of vegetable oils has increased rapidly over the last 20 years, from around 75 million tonnes in 1997/1998 to 197 million tonnes in 2017/2018 (Figure 8). Global vegetable oil production is dominated by four oils, namely: palm, soybean, rapeseed, and sunflower, which together account for 86% of the world's vegetable oil market.

Over 80% of palm oil, the world's largest source of vegetable oil, is produced in Indonesia and Malaysia, accounting for 35% of total production. The huge growth of palm oil has occurred because it is the highest yielding vegetable oil crop worldwide. While one hectare of land can produce just 0.38 tonnes per year of soybean oil, 0.48 tonnes of sunflower oil, and 0.67 tonnes of rapeseed oil, the same hectare can produce more than 3.7 tonnes of palm oil [41].

Regarding the other major oils, Brazil and the USA are the main producers of soybean oil, which accounts for 28% of overall vegetable oil production, while around 60% of the rapeseed oil production occurs in the EU and China. Finally, the vast majority of sunflower production occurs in Ukraine, Russia, and EU [41].

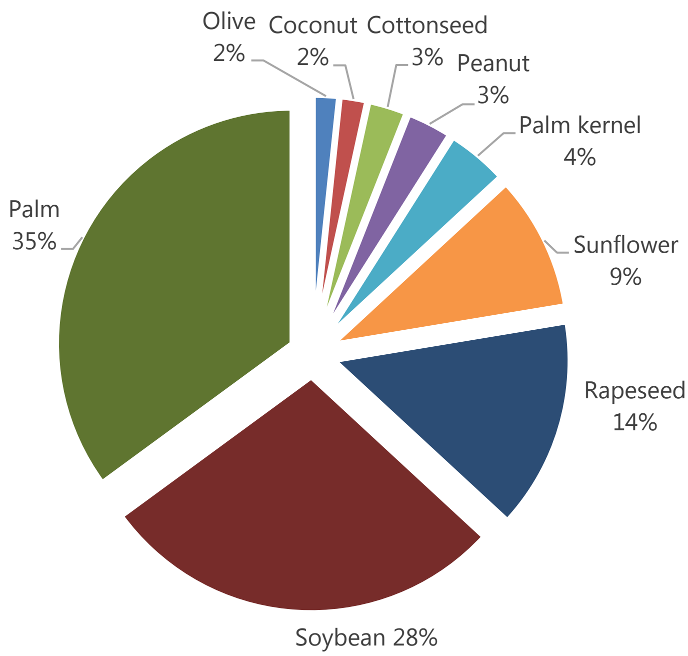


Figure 9: Global vegetable oil production (%) by source (2017/2018). Source: USDA

4.1.2 Competing Markets

The growth rate of vegetable oil consumption has been larger than the growth of the world population. Traditionally, these oils were produced for human consumption, but the percentage used globally for other purposes has increased from 10.5% in 1999/2000 [42] to 24% in 2017/2018 [43]. Non-food uses now include: the production of animal feed, soap, personal care products, biodiesel, paints, lubricants and greases [44].

Industrial use of vegetable oils varies widely between regions. In the EU, rapeseed oil is the main vegetable oil used in biodiesel production, which equates to around 60% of total EU rape oil production[17] [45]. In the USA, the use of rapeseed oil in non-food processes is much lower, with soybean oil being the most prominent in biodiesel production; however, in South East Asia, more than half of the oils consumed are destined for industrial purposes, resulting in the consumption of large quantities of palm oil [44].

Figure 10 presents trends in food and industrial use of the four major vegetable oils in the EU, while Figure 11 presents the quantities of vegetable oils used specifically for biodiesel production. By combining those figures, it is evident that the majority of vegetable oil used in the EU for industrial purposes is for biodiesel production, which has created fluctuations in supply.

Figure 10: EU trends in food and industrial use of the four major vegetable oils. Source: USDA

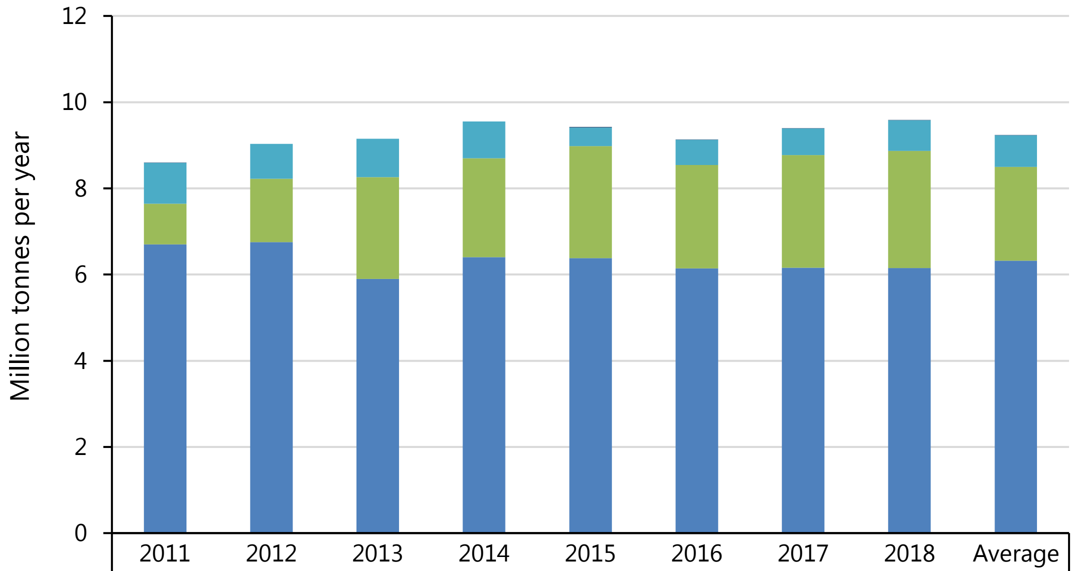
Rapeseed is the vegetable oil that is used in higher quantities in the EU. The industrial use of rapeseed oil has grown tremendously since 2002/2003, peaking at 7 million tonnes in 2009/2010, and accounting for around 70% of the overall use. Most of the rapeseed oil used in industry goes to

[17] In the UK the picture is considerably different, as biodiesel plants principally use waste oils and secondarily tallow as feedstock.

biodiesel production, with an average of 6.3 million tonnes per year (since 2011), allowing around 0.7 million tonnes to be used for other industrial purposes.

As is the case for rapeseed oil, palm oil's industrial use has increased significantly since 2002/2003, surpassing its use as a food product in 2013/2014 due to slower growth in that sector. In the period 2011 to 2018, approximately 70% of palm oil used for industrial purposes was for biodiesel production, while the rest is used in animal feed as well as in personal care and cleaning products, for the production of surfactants, glycerine and emulsifiers [46].

With regards to soybean oil, its use for industrial purposes soared between 2002 and 2006 but since then it appears to have been in decline. In the period 2011 to 2018, around 76% of soybean oil used for industrial purposes was for biodiesel production, with the remainder being used in cosmetics and paint production [47]. Finally, as shown in Figure 10, the use of sunflower oil in industry is limited, mainly due to its properties and its positive health benefits when used in the food sector.



	2011	2012	2013	2014	2015	2016	2017	2018	Average
sunflower oil	10	0	0	0	15	5	5	5	5
soybean oil	950	810	890	850	430	590	620	710	731
palm oil	940	1470	2,360	2,300	2,600	2,400	2,610	2,720	2,175
rapessed oil	6,700	6,750	5,900	6,400	6,380	6,140	6,160	6,150	6,323

Figure 11: Vegetable oils used for biodiesel production in EU [48]

4.1.3 Projected global production and demand

Global oilseeds production is expected to grow at around 1.5% per annum, well below the growth rates of the last decade. Crushing of soybean and other oilseeds into meal (cake) and oil, will continue to dominate the market and is expected to increase faster than other uses, particularly the direct use of oilseeds in food and animal feed industry[18] [49].

Demand for vegetable oils is expected to increase, but at a slower pace than in the last decade, mainly due to slower growth in per capita food consumption in developing countries and the projected

[18] Overall, more than 86% of the world's oilseed production is projected to be crushed in 2027

stagnation in demand as feedstock for biodiesel. Brazil and the United States will remain the largest soybean producers, with similar volumes, while vegetable oil exports will continue to be dominated by Indonesia and Malaysia. The increases in soybean and palm oil production will depend on replanting activities and the availability of additional suitable land [49].

With regards to palm oil, for the development of its production in Malaysia and Indonesia, the cultivated land area has increased by 150% and 40% over the last decade, respectively. It is estimated that 17% of the new plantations in Malaysia and 63% of those in Indonesia came at the direct expense of tropical forests over the period 1990–2010, and up to 30% of this expansion occurred in peat soils, resulting in large CO_2 emissions [50]. Despite the slowdown in the expansion of the oil palm area, growth is still projected in Indonesia (1.8% p.a. vs. 6.9% p.a. in the previous decade) and Malaysia (1.4% p.a. vs. 1.3% p.a.) [49]. It should be noted however, that according to FAO, Indonesia has 18.2 million hectares of available land, 10 million hectares of which are currently planted, and therefore might face a shortage of land for sustainable oil palm production. Malaysia with 2.1 million hectares of available land and 4.6 million hectares currently under cultivation has already outgrown its sustainable area[19] [50]. This suggests that the projected increase in palm oil production will have to come as a result of increasing crop yields, in order to remain sustainable. These yield increases are, however, deemed unrealistic within the timeframe covered by the projections.

Large areas of land have been converted to soybean plantations over the last decades. In 1961 the soybean area was around 24 million hectares worldwide, which grew to 107 million hectares in 2012, resulting in the conversion of forests and the loss of biodiversity. The greatest conversion to soybean crops can be seen in Brazil, where the total soybean area increased from 240,000 hectares in 1961 to 25 million hectares in 2010 [51]. Global soybean production is expected to continue to grow by 1.5% per annum between 2018 and 2027, but at a slower pace than in the last decade, when the growth rate was 4.8% per year.

Brazil and the United States will remain the largest soybean producers and are expected to maintain similar levels of production over the next decade, with production in both cases reaching around 130 million tonnes in 2027 [49]. Finally, it should be noted that according to OECD-FAO Agricultural Outlook, 55% of the overall soybean production growth projected for the period 2018-2027, will come from yield increases [49], which means that the remaining 45% of growth will rely on additional land.

The global uptake of vegetable oils as feedstock for biodiesel production will remain virtually unchanged by 2027 (0.3% p.a. growth), as compared to the 8.5% p.a. increase recorded over the previous decade, when biofuel support policies were taking effect. In general, national targets for mandatory biodiesel consumption are expected to increase less than in previous years, while low crude oil prices are likely to limit non-mandatory biodiesel production. In addition, waste oils, tallow and other feedstocks are increasing their share in the production of biodiesel to a large extent due to specific policies favouring wastes and their availability [49]. Similarly, support mechanisms for

[19] Area expansion could be constrained by new legislation seeking to protect the environment. Roundtable on Sustainable Palm Oil (RPSO), and the European Union as well as the United States have also set-up specific sustainability criteria on feedstock imports for biofuel production. However, RSPO-certified palm oil continues to be a niche product, holding about only 15% of the market, half of which is marketed as conventional palm oil, since demand for certifies oil is still too low [50].

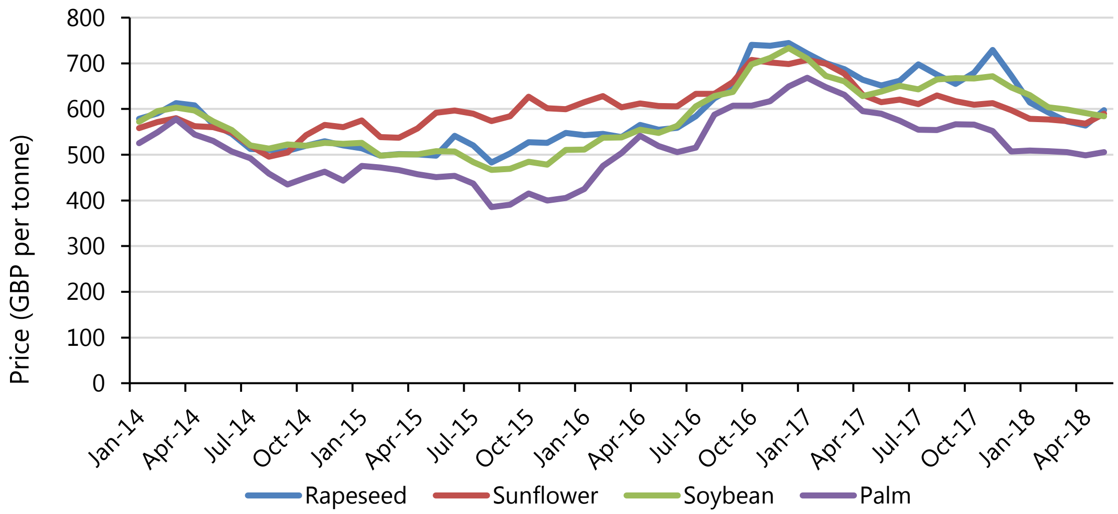
renewable power generation in the UK, such as the Contracts for Difference (CfD) scheme favour use of waste-oils and restrict the use of vegetable oils through strict sustainability criteria which comprises GHG emissions limits and land criteria limiting where vegetable oils can be produced and sourced for this market. As a result, no significant competition is expected from the renewable power sector in the UK, or more widely at EU level.

Given the shift of focus in the EU to waste oil and tallow, the use of vegetable oil for biodiesel production is expected to account for 39% of domestic vegetable oil consumption by 2027, declining from a current share of around 41% [49]. As a consequence, the area planted to oilseed rape in the EU, which accounts for around 62% of the vegetable oils used in the production of biodiesel currently, could drop by as much as 8% to 6 million hectares over the next 13 years [52]. Beyond 2027, a more rapid transition to waste-derived and developmental fuels supported more heavily by the RTFO is expected, so demand on vegetable oils will decline further. This could potentially offer increased availability for other markets or reduce pressure on agricultural land from non-food applications.

4.1.4 Economics

Many vegetable oils are used for both food and industrial purposes. An important factor determining which edible oils are used for industrial purposes is their price [53]. Figure 12 shows the price trend of the four major vegetable oils, based on their production quantities, namely: palm, soybean, rapeseed, and sunflower. Palm oil is typically cheap, with soybean oil traditionally holding a higher price premium, while sunflower and rapeseed oil are typically holding a small price premium over soybean oil due to their superior quality and availability.

Other edible oils, such as olive oil, trade at a significantly higher premium. High prices can restrict the use of certain oils in non-food applications, where competitiveness with fossil derived alternatives is a key factor affecting uptake, which makes palm, soybean, rapeseed, and sunflower oils, more attractive and available for industrial use.



Rapeseed Oil; Crude, fob Rotterdam. Sunflower Oil; US export price from Gulf of Mexico. Soybean oil (Any origin), crude, fob ex-mill Netherlands. Palm oil (Malaysia), 5% bulk, c.i.f. N. W. Europe.

Figure 12: Vegetable oil prices since 2014. Source of data: Index mundi

4.1.5 Emissions

There are a limited number of studies where vegetable oil has been used directly as a fuel in boilers, without first being converted into biodiesel via hydrogenation or transesterification. Advantages of using straight vegetable oil (SVO) include lower processing requirements, but disadvantages include cold weather problems and high viscosity as shown in Appendix B. Despite this, interest in the use of straight vegetable oils has been growing, particularly in India and West Africa [54][55]. Schmidt et al. [56] compared the lifecycle GHG emissions of five vegetable oils and found emissions were highly dependent on the feedstock and associated land use change. GHG emission factors ranged from 262 kg CO_2e per tonne of refined oil for rapeseed oil to 4,717 kg CO_2e per tonne for peanut oil.

From the few studies available, authors have presented mixed results when comparing emissions of air pollutants from boilers burning vegetable oils and blends in place of heating oil and a review of these studies was carried out by Oumer et al. (2018) [57]. Huang et al [58] demonstrated that 5-30% castor oil may be blended with gas oil and burned in a commercial 300 kW_{th} oil boiler, with minimal effect on NOx and SO_2 emissions. San José Alonso et al. [59], and references therein, trialled blends of virgin soya, sunflower and rapeseed oil in a 27 kW domestic boiler. Results showed an increase in boiler efficiency with blend percentage (up to 40% in gas oil), a significant decrease in CO and a slight increase in NOx. The authors also found that the composition of fatty acids in the feedstock can affect the burner operating conditions, particularly linolenic acid content which is higher in rapeseed and soybean than in sunflower oil [60]. Daho et al. [32] found that some virgin vegetable oils such as cottonseed oil require a substantial pre-heating step, raising the oil temperature to as high as 125°C. In comparison to heating oil, cottonseed oil was found to emit significantly more CO, slightly more NOx and significantly less SO_2.

Esarte et al [61] burned a blended heating oil containing a virgin vegetable oil mixture of rapeseed, palm and jatropha oil in a 30 kW boiler. It found that NOx emissions reduced slightly as a result of the fuel's lower nitrogen content.

4.2 Used Cooking Oils

Used cooking oil (UCO) is waste vegetable oil collected from industrial, commercial and domestic users. For domestic heating purposes, used cooking oil can either be refined into a product suitable to be used in dedicated waste oil boilers or can be converted into biodiesel, which can be mixed with kerosene or used neat, in converted or dedicated boilers, respectively.

Currently, most of the UCO available in the UK is supplied for biodiesel production, for road transport purposes. The Renewable Transport Fuels Obligation (RTFO) supports the use of biofuels that meet the sustainability criteria, described in Renewable Energy Directive (RED); the criteria is two-fold, setting GHG emissions limits and restricting the type and previous use of land from which biofuel feedstocks can be sourced. The RTFO covers biofuels used in transport and in non-road mobile machines, by awarding Renewable Transport Fuel Certificates (RTFCs) to fuel suppliers who are obliged to supply increasing proportions of renewable fuel in their overall fuel mix over time; RTFCs can be traded between producers and suppliers to ensure obligations can be met. To encourage the use of fuels that represent significant environmental advantages some biofuels, such as waste-derived biofuels, are double-counted and issued with double the number of RTFCs per litre. Biodiesel derived from used cooking oil falls within this category.

In the short term, the demand for UCO biodiesel is expected to increase, as the mandate for renewable transport fuels in the overall fuel mix increased from 4.75% to 7.25% in April 2018[20]. The rise in the mandate is expected to be met primarily by biodiesel derived from UCO, because of a 4% cap on the contribution that can come from crop-based biofuels in 2020, which will decline steadily to 2% in 2032, and due to the fact that the second-generation ethanol is not yet competitive[21].

Other existing markets for UCO in the UK include applications in the oleochemicals industry, energy from waste, or animal feed; however, demand is less as no direct support measures are available.

4.2.1 Arisings and availability

The majority of UCO generated in the UK is collected from public sector bodies such as Councils, Local Authorities, schools and prisons, or from commercial food outlets and the hospitality sector [62]. UCO is typically collected, processed and redistributed by a small number of independent brokers in the UK. The UK Sustainable Bio-Diesel Alliance (UKSBA) estimated total arisings of 200-275 million litres per year in the UK, of which 73% is sourced from the commercial sector and the remainder from the residential sector [63]. In the EU-28, annual vegetable oil consumption is currently is 26.6 kg per capita on average [64]. This is forecast to reduce slightly to 25.6 kg per capita in 2027. Globally, consumption is forecast to increase from 21.3 kg per capita to 23.1 kg per capita; meaning an additional 33.9 million tonnes of vegetable oil per year will be consumed by 2027 [64].

According to the latest RTFO annual report, 119 million litres of UCO-derived biodiesel was delivered to the UK transport sector in the period 2017/2018, sourced from within the UK (although a significant proportion of the feedstock is imported). In addition, 50 million litres of UCO biodiesel are exported each year, mainly to the Netherlands and France [62]. The biodiesel yield from UCO varies widely from 70% to up to 98%, depending on a number of factors including processing time, temperature, choice of catalyst and quality of the UCO [65]. Assuming a typical yield of 92-97% in the UK [66], and taking into consideration the alternative outlets for collected UCO in the oleochemical industry (25,000 tonnes) and energy from waste (10,000 tonnes) [67], this suggests that the majority of UCO collected has readily established markets. However, UCO can be imported and hence supply could be increased, but many other EU member states are utilising their domestic supplies in similar ways. Steady growth in demand for road transport is expected to at least 2027 as described above, but beyond that an accelerated transition to waste-derived and developmental fuels supported more heavily by the RTFO is expected, so demand on UCO from this sector will decline further, potentially increasing availability for other markets. However, at the same time other transport sectors and other countries are considering UCO to meet their policy objectives, so availability for heating may remain constrained.

A recent study carried out by GREENEA revealed that the European and UK UCO market is already mature with limited growth opportunities, and in order to secure enough feedstock, waste-based biodiesel producers will have to look for alternative sources such as collection of UCO from households[22], and imports from overseas [68]. Despite 50-75 million litres of UCO being produced in

[20] The mandate will increase further to 9.75% in 2020 and to 12.4% by 2032.

[21] www.gov.uk/government/news/new-regulations-to-double-the-use-of-sustainable-renewable-fuels-by-2020

[22] Most of the sourced cooking oil is collected from commercial operations, as cooking oil in the domestic environment is rarely collected in the UK and EU.

the UK each year by households [69], small volumes are currently being collected in the UK and EU due to collection difficulties and high operational costs [68]. A recent International Council on Clean Transportation (ICCT) report estimates that of the 800,000-900,000 tonnes produced per year, less than 50,000 tonnes of UCO are currently collected from households across Europe. This study estimates that by 2030, in the most optimistic scenario, around 200,000 tonnes per year could be collected with active and continuous support from Member States, as household collection has to be organised from scratch in the majority of EU countries [70]. Section 3.1.2 of the Waste Strategy for England set a commitment to legislate that, subject to consultation, '*every householder and appropriate businesses have a weekly separate food waste collection*' service from 2023. Currently most residential sector UCO is disposed of with municipal solid waste or with kitchen wastewater, where it can cause drain blockages. UCO disposal in landfill is illegal under the EU Landfill Directive 99/31/EC and Environmental Permitting Regulations 2010. Furthermore, waste cooking oil generated through the cooking of meat or fish is classified as category 3 under the Animal By-Products (Enforcement) Regulations 2013 and requires separate disposal. The ABP regulations do not currently apply to imported UCO. Collection is not generally available for domestic premises, so UCO must be deposited at suitable civic amenity sites. For example, Nottinghamshire County Council has twelve recycling centres with UCO collection tanks, which are delivered to Living Fuels Ltd in Nottingham and used to generate electricity.

With regards to imports of UCO, Greenergy, a UK biofuel producer, acquired 100% of the shares of a UCO exporter, Rexon Energy, who is based in Singapore, to provide raw materials for its biodiesel manufacturing operations in the UK, which shows that there are opportunities for increasing availability with imported UCO [71]. However, the quantities offered are decreasing because of the rising local demand in other countries. Asia, the largest supplier of UCO to Europe, is currently investing in biodiesel production, and the quantities available for export are expected to reduce [68].

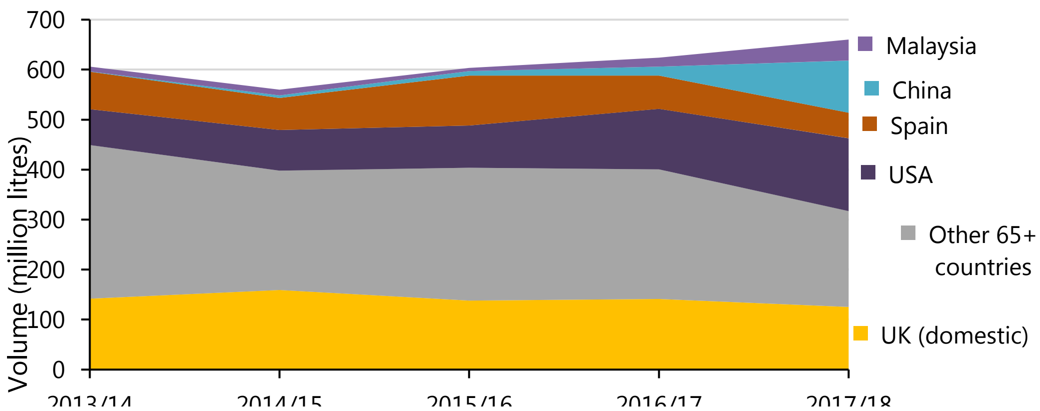


Figure 13. Country of origin of UCO used to produce biodiesel consumed in the UK under the RTFO by year April 2013 – April 2018 [72].

There are currently no established supply chains for UCO to be used directly or after a refining step to supply dedicated boilers for off-gas grid homes in the UK. In order to progress this sector additional investment would be required in fuel storage and delivery infrastructure, to enable storage and transport of different oils, potentially on the same vehicles. Additional investment in bulk storage facilities at central collection and distribution hubs would be necessary, to ease the transport burden in both cost and carbon terms, and to improve distribution efficiency.

4.2.2 Economics

Prices paid for UCO are dependent on quality, source, and on seasonal variations. UCO suppliers in urban areas, for example, will generally be paid more than those in rural areas as the cost of collection in more remote areas might negate the price for the feedstock [62].

With regards to the biodiesel market, higher quality UCO can be sold to processors by collectors for around 45-60 pence per litre but lower quality UCO is sold for around 25 pence per litre [69]. Moreover, during the winter months, biodiesel is reportedly used less in transport, or at lower blends, due to fears over the cold flow ability of higher blends and the suitability to colder ambient temperatures. Driven by demand, biodiesel producers will therefore pay less for UCO in winter months (around 40 pence per litre, or £400 - £500 per tonne) and more in the summer months (around 60 pence per litre or between £600 and £700 per tonne) [69].

The price of UCO naturally increases along the supply chain as the UCO is continuously processed to improve its quality and suitability for market. According to Ecofys estimations in 2013, restaurants sell UCO for a maximum of £260/tonne while small UCO collectors could charge up to £470/tonne for filtered UCO. Larger UCO collectors and melting plants can charge £690-760/tonne for UCO that is purified and ready for biodiesel production while the final product, UCOME (biodiesel derived from UCO), was sold for around 86 pence per litre (£960/tonne) in 2013 [62].

UCO is currently trading at £420-470 per tonne [73] and is in high demand due to the double counting of this waste-based feedstock. RTFO data shows that UCO consumed in the UK transport sector is currently sourced from 70 different countries. As shown in Figure 14, the fastest growing sources of UCO and UCOME are the USA, China and Malaysia.

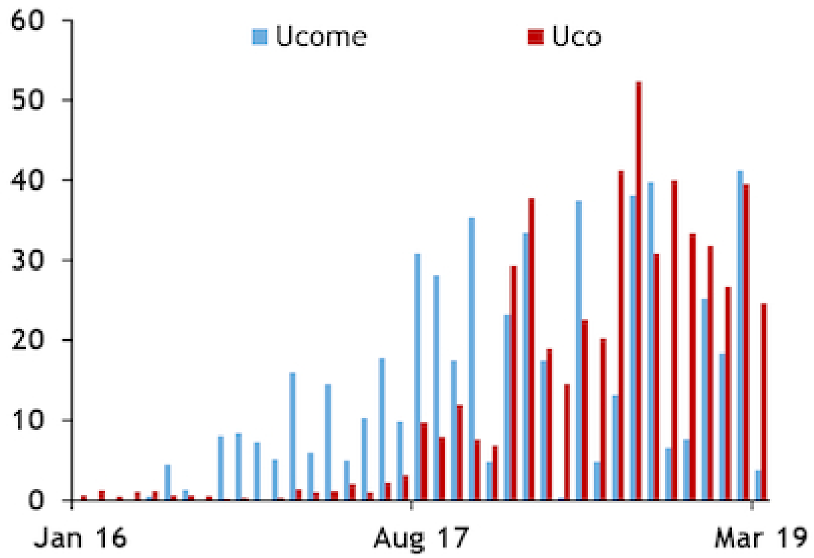


Figure 14. Exports of UCO and UCOME from China to the EU (thousand tonnes), January 2016 – August 2018. Source: Argus Media [74]

Particularly noteworthy is the rapid growth in Chinese untreated UCO exports to European Union, which has increased by a factor of five in just one year, as shown in Figure 14.

4.2.3 Emissions

As with virgin vegetable oil, there are a limited number of examples where UCO has been used directly in boilers. However, there is a body of evidence showing that UCO may be burned directly in modified diesel engines. Li et al [75] found that the lifecycle greenhouse gas emissions for straight UCO could be up to 52% lower than UCO-biodiesel, at 68.7 kg CO_2e per tonne of refined oil, due to intensive energy consumption in the transesterification process.

UCO would need to be 'ultra-refined' in order to be used in domestic heating systems to avoid blocking fuel filters and would require pre-heating to lower the viscosity. UCO has a very low sulphur content in comparison to heating oil and therefore low SO_2 emissions. Esarte et al [61] found that a blend of 50% UCO in heating oil could reduce NOx emissions by up to 17%, primarily due to the lower fuel nitrogen content. However, the authors noted possible issues with suitability of UCO as a domestic boiler fuel in comparison to other bioliquids due to the higher density. There may also be limited uptake of UCO as a domestic heating fuel due to issues with odour; it is recommended that UCO storage tanks and boilers be sited away from the property, perhaps in an outbuilding, due to odours from the fuel.

4.3 Biodiesel (FAME)

To date, the predominant use of Fatty Acid Methyl Esters (FAME) of vegetable oils has been for use as biodiesel supported under the RTFO and to a lesser extent for renewable power generation, supported historically under the Renewables Obligation (RO), as is the case for UCO.

In accordance with the RTFO, since 1 January 2019 road diesel must contain up to 8.5% biodiesel. Biodiesel can be blended with heating oil in a similar way and burned in existing oil boilers with relatively few technical challenges. Other than modifications to the burner, injectors and material compatibility throughout the fuel supply lines, the technical potential of biodiesel as a boiler fuel has been well demonstrated. However, there is a maximum blend level above which more significant modifications to the system are required.

Biodiesel (FAME) should meet the requirements of BS EN 14214 standard and be produced under strict quality assurance systems to achieve consistent quality and fuel properties. In addition, for biodiesel and kerosene blends, OFTEC has worked with industry to develop a standard, the "OPS 24 – Bio-liquid/Mineral Fuel Blend Standard", for blending 30% biodiesel with 70% Kerosene (B30K), specifying the fuel characteristics to be met for use in converted kerosene boilers [76].

BS EN 14214 sets climate-dependent requirements for the cold filter plugging point (CFPP) of B100 FAME. For temperate climates, the maximum CFPP ranges from +5°C for Grade A and -20°C for Grade F. It is well understood that the feedstock used for biodiesel production has significant effect on the oxidation stability and cold weather performance of the fuel, both neat and blended.

The impact that this has on the heating sector is potentially more severe than in the transport sector, given larger fuel tanks and lower fuel turnover. Biodiesel produced from feedstocks with relatively high levels of unsaturated fatty acids such as rapeseed and sunflower oil are more prone to oxidation, but exhibit better cold flow properties, as shown in Figure 15. This can have a significant effect on the suitability of a given feedstock for a market in a temperate climate, and therefore on the fuel price and availability. For example, the CFPP of FAME varies from -10°C for canola oil to +12°C for palm oil [77].

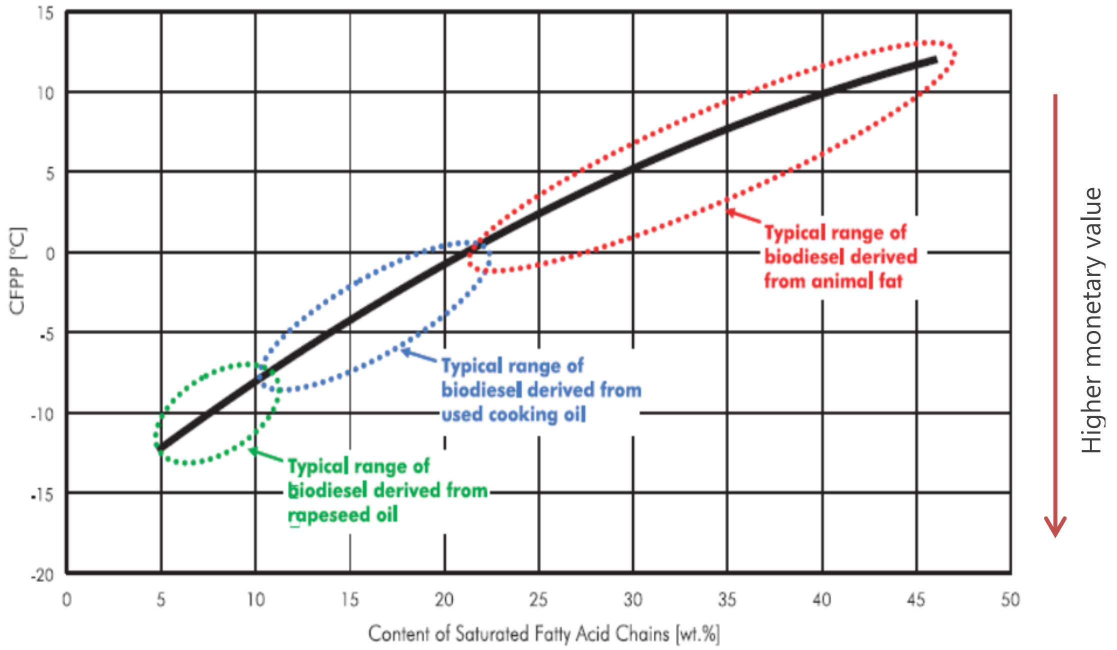


Figure 15. Relationship between cold filter plug point (CFPP) and fatty acid content for different types of biodiesel [78].

The CFPP of used cooking oil, which is the most common biodiesel feedstock in the UK, is -9°C but the oxidation stability is 75% lower than for palm oil [77]. Given that kerosene naturally has a very low CFPP, blending can greatly improve cold weather problems; blends up to B30K are expected to meet the -12°C winter limit for gasoil [76][79]. In addition, the use of additives is recommended under BS 2869:2017 in order to enhance the oxidation stability of FAME. The use of antioxidant additives combined with a very clean storage environment may increase longevity of B30K up to three years and B100 up to one year [80].

Another measure of the cold weather susceptibility of a fuel is the cloud point, which is given together with CFPP for different fuels types in Appendix B. The cloud point is the temperature at which waxes begin to separate in the fuel, giving a cloudy appearance. Concawe (2009) [30] guidance suggests that B100 should be stored at temperatures at least 6°C higher than the cloud point at all times.

4.3.1 Arisings and availability

The vast majority of biodiesel available in the UK is blended with fossil-diesel and burnt in standard diesel engines, supported by the RTFO. Biodiesel supplied in the UK for road transport, from April 2017 to April 2018, totalled 802 million litres; 622 million litres of which met the RED sustainability criteria (GHG and land criteria). However, biodiesel demand in the UK for transport is expected to rise as a result of the increase in the RTFO mandate for biofuels from 7.25% in April 2018 to 8.5% in

January 2019[81], as shown in Figure 16. The mandate will increase further to 9.75% in 2020 and to 12.4% by 2032 and that factor may limit the availability of biodiesel for alternative uses[23].

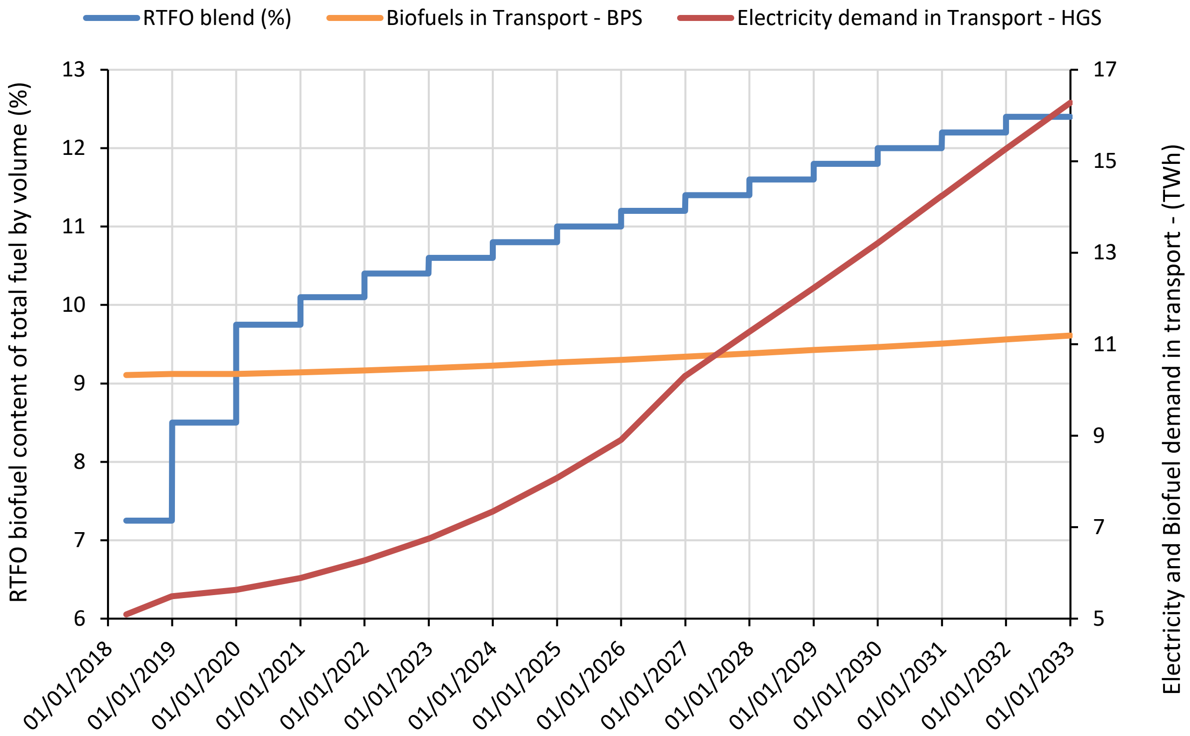


Figure 16. Biofuel blend requirements in the UK under the RTFO and projected demand for biofuels and electricity in the transport sector to 2033. BPS = Baseline Policies Scenario, HGS = High Growth Scenario

These increases in the mandate are expected to be met primarily by waste-derived biodiesel, due to the 4% cap on the contribution from crop-based biofuels and the fact that second generation bioethanol is not yet commercially available. Alternative markets include: the use of biodiesel as an aviation fuel[24], as a remediation agent to treat shores polluted with heavy oils, as well as a substitute for many petroleum solvents [82]. *Under the UK Plan for Tackling Roadside Nitrogen Dioxide Concentrations*, the Government will end the sale of new petrol and diesel cars by 2040. There have, however, been calls to bring forward this deadline to 2032 to be more in line with other European countries such as Ireland, Denmark and Germany. Additionally, there are other pressures on drivers of diesel cars such as charges in Clean Air Zones and Ultra Low Emission Zones. Hence between 2018 and 2030 there is likely to be a more significant uptake of electric and low-emission vehicles.

The UK has six large-scale biodiesel production plants with a total capacity of 657 million litres per year. Table 7 presents details of the largest biodiesel plants, including information on their location, year of operation, capacity, and feedstock mix. It is clear that none of these plants depend on edible oils as the main raw material, and the majority of their biodiesel is waste-derived. In addition to the

[23] It should be noted that biofuels derived from waste/residues are double counted, in terms of their contribution to meet the above-mentioned targets.
[24] Due to its low-temperature properties biodiesel is suitable for only lower-flying aircraft

larger biofuel production plants, there were over 60 other companies registered as producers in the RTFO Operating System (ROS) in 2012. Most of these companies are significantly smaller in scale, typically ranging from a few thousand litres to over a million litres of biofuel production per year and most make biodiesel from used cooking oils (UCO). Many of these companies are also involved in the collection of UCO, and often started out with a UCO collection business [83].

Table 7: UK larger scale operational biodiesel plants [83]

Company	Location	Year of Operation	Capacity (Million Litres)	Feedstock Mix
Argent Energy	Motherwell, Scotland	2005	60	UCO, tallow, sewage grease
Harvest Energy *(formerly Biofuel Corporation)*	Seal Sands, Teesside	2006	284	Primarily waste oils
Olleco *(formerly Convert 2 Green)*	Middlewich, Cheshire	2007	20	UCO
Greenergy	Immingham, Hull	2007	220	Waste Oils
Ennovor	Bromborough	2010	57	Waste Oils
Olleco *(formerly Agri Energy)*	Bootle, Merseyside	2012	16	UCO
FutureFuel	London	2016	12	UCO

RTFO statistics report that only 25% of the biodiesel delivered to the UK and intended for transport (total amount: 802 million litres), originated from the UK during the 2017/2018 period [72]. In addition, around 50 million litres per annum are exported, suggesting that production capacity in the UK, to a large extent, is currently underutilised. Appendix A illustrates the origin of biodiesel used in transport during the 2017/2018 period.

Both import and export have risen significantly in the EU-28 in the last 10 years, but growth has been comparatively slow in the UK, as shown in Figure 17. Reduced import duties on foreign biodiesel entering the EU have led some companies to reduce output in Europe. Soybean biodiesel from Argentina and palm oil biodiesel from Indonesia may be up to 25% cheaper than EU rapeseed biodiesel. However, the next European Renewable Energy Directive (REDII), which covers the period from 2020 to 2032, is likely to result in a significant reduction in palm oil demand and consumption as a result of revisions to the sustainability criteria, whereby the European Commission is seeking to phase out feedstocks associated with high land use change impacts by 2030.

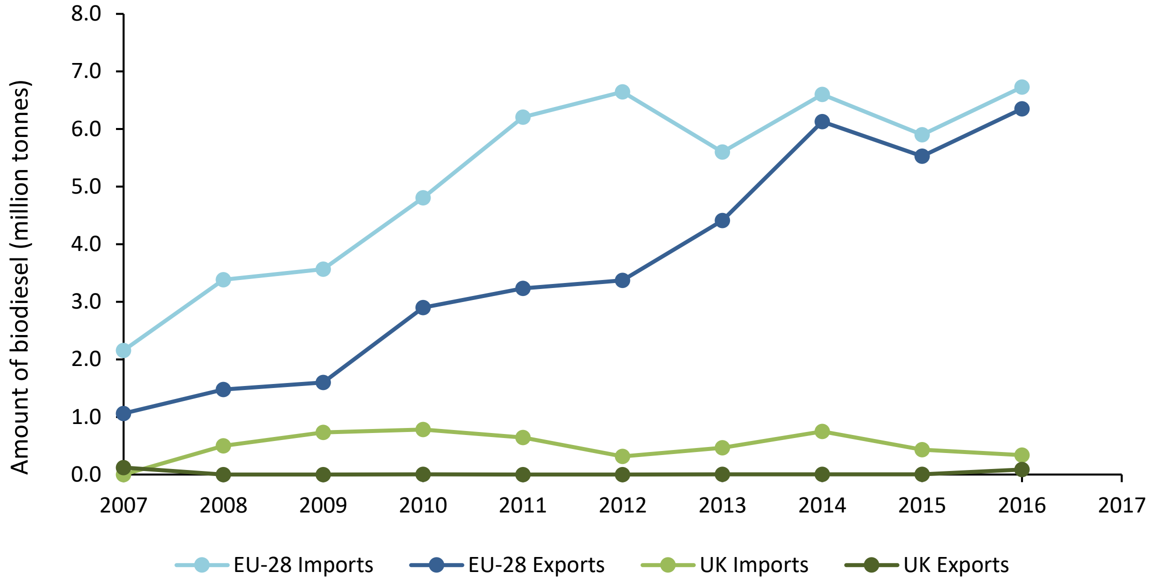


Figure 17. Imports and exports of biodiesel in the UK and EU-28 since 2007. Data sourced from Eurostat [84].

4.3.2 Economics

The major factor that influences the economics of biodiesel production is the price of feedstock, regardless of the technology type. Edible oil feedstocks are expensive due to competition with the food market, while non-edible vegetable oils, waste cooking oil and animal fats can be purchased at a relatively low cost [82],[85].

Process type is another factor which can significantly affect the economics of production [82]. Among the conventional technologies, the acid catalysed transesterification reaction is the most cost effective to produce fuel grade biodiesel from cheaper feedstock with higher fatty acid content. Acid catalysts can catalyse both esterification and transesterification reactions without feedstock pre-treatment steps. This economic feasibility is manifested by having lower total manufacturing cost and lower biodiesel breakeven price [86].

Other factors that can significantly affect the viability of a biodiesel production plant include the capacity of the plant, the selling price of biodiesel and the selling price of glycerol, a co-product of production [86].

According to Zivkovic et al. (2017), depending on the raw material and plant capacity, the cost of biodiesel production can range from approximately 0.2 USD/litre, for waste and non-edible oils, to over 2 USD/litre for palm and sunflower oils, which is about 1.5 times higher than the price of diesel fuel in the USA [82].

Currently, there are no well-established supply chains for pure biodiesel or suitable biodiesel blends for residential heating, as the market for B100 dedicated boilers and those suitable for handling blends is limited. As has been experienced in the fuel sector, conversion or adaption of existing delivery fleets, vehicles and infrastructure would be the most likely solution should the biodiesel heating market expand in the future.

Fatty Acid Methyl Ester (FAME) biodiesel trades under a range of names, as shown in Table 8. Since the feedstock type significantly affects the cold weather properties and GHG savings of the final product, biodiesel produced from certain feedstocks have a higher trade price. Assuming that a maximum CFPP of -10° is required for B100 used in off-gas grid domestic heating applications, only Rapeseed Oil Methyl Ester (ROME) and FAME -10°C are suitable. This therefore limits the availability of biodiesel and also increases the price, since ROME is currently 51% more expensive than POME (Palm Oil Methyl Ester).

Table 8. Comparison of biodiesel prices with feedstock, cold filter plug point and greenhouse gas savings. Data source: Argus Media [73]

Trade name	Feedstock	Cold filter plug point (CFPP)	GHG savings[(A)]	Bid spot price at 02/01/2019 (GBP per tonne)
ROME fob ARA range	Rapeseed oil	-12°C	57%	863
FAME 0°C CFPP fob ARA range	Any vegetable oil	0°C	57%	641
UCOME 90pc GHG savings fob ARA range	Used cooking oil	0°C	90%	782
POME fob ARA range	Palm oil	15°C	60%	573
SOME fob ARA range	Soya bean	-4°C	60%	684
FAME -10°C CFPP fob ARA range		-10°C	57%	841
FAME 0°C CFPP cif Genoa	Any vegetable oil	0°C		637
TME fob ARA range	Tallow	12-13°C	60%	754

(A) Minimum greenhouse gas savings compared to a fossil fuel comparator of 98.3 gCO_2e/MJ under the EU RED Directive.

4.3.3 Emissions

According to SAP 10.0 [16], the lifecycle GHG emissions for B100 range from 38 g CO_2e/kWh for biodiesel produced from any biomass feedstock to 18 gCO_2e/kWh for that produced from vegetable oil feedstocks. The emissions factor for B30K or B30D is 220 gCO_2e/kWh. In comparison, the emission factors given in the UK GHG Conversion Factors for Company Reporting 2018 [87] are 35.7 gCO_2e/kWh for UCO-biodiesel and 53.1 gCO_2e/kWh for tallow-biodiesel, with an average value for mixed source biodiesel of 37.8 gCO_2e/kWh. Li et al [75] reported a GHG emission factor of 13.7 gCO_2e/kWh for UCO-biodiesel. Biodiesel used as a transport fuel also carries an additional GHG burden relating to indirect land use change (ILUC), where virgin vegetable oils are the feedstock.

From the few studies available, authors have presented mixed results when comparing emissions of air pollutants from boilers burning biodiesel and blends in place of heating oil and a review of these studies was carried out by Oumer et al. (2018) [57]. One of the earliest studies in this area was carried out by Krishna (2004) [88] which found both CO and NOx could be slightly reduced with higher biodiesel blend ratios.

Macor and Pavanello (2009) [89] trialled a 400 kW boiler with heating oil and B100 and found the differences in emissions relative to heating oil, as illustrated in Table 9 below.

Table 9. Percentage change in emissions of air pollutants for a boiler burning B100 compared to heating oil. Data from Macor and Pavanello (2009) [89].

	CO	NOx	SO2	PM	PAH
Biodiesel trial 1	-88%	+1%	*	-59%	-99.5%
Biodiesel trial 2	-91%	-5%	*	-77%	-98.8%

*SO_2 emissions were found to be higher but this was an anomalous result as sulphur content of biodiesel is usually far lower than heating oil (see Appendix B)

Esarte et al [61] tested biodiesel blends with gas oil and kerosene in two domestic 30 kW boilers. It was found that NOx emissions for a B30K blend using a mixed-feedstock biodiesel were in the range 101-109 mg/kWh, whereas emission factors for a B50K were 83-95 mg/kWh. CO emissions were below 20 mg/kWh and SO_2 emissions were very low.

González-González et al. [90] tested blends of 10%, 20%, 30% and 100% sunflower-biodiesel with gasoil in a 26 kW domestic oil boiler. The study found that CO emissions were generally low for blends up to 30% but increased significantly for B100. Reduced efficiency and higher emissions may occur if the fuel air requirements and combustion stoichiometry are not optimised for the higher fuel oxygen content of biodiesel. Moreover, Dong-Shik et al. [91] showed that the feedstock used for biodiesel production has a significant effect on PM, NOx and CO emissions in engines, although more research is needed in this area for boiler applications.

4.4 BioLPG (biopropane)

Traditionally, LPG consists of propane and/or butane, which are typically produced as a by-product of crude oil refining and natural gas processing. Biopropane or bioLPG is the term commonly used to describe LPG that is derived from biomass, which is chemically identical to the fossil-based LPG. Bio-LPG is a drop-in fuel which can be used in conventional LPG domestic boilers without the need for any modifications to boilers, appliances or infrastructure. This means that for properties which already use LPG boilers[25], bioLPG can be simply mixed with fossil LPG or supplied in pure form and distributed to consumers through existing distribution channels. Because of this, some have claimed BioLPG to be the lowest cost and most practical bioliquid for off-grid heating [92].

LPG is currently used as an energy source for heating and cooking in off-gas grid homes and businesses. Moreover, LPG is used in the UK agricultural sector to power portable equipment (e.g. water pumps), non-road mobile machinery (e.g. forklift trucks), and also agricultural processes (e.g. crop drying, animal rearing and greenhouse heating). Finally, in UK industrial applications, LPG is used for process heat and power while in the infrastructure sector it is mainly used for maintenance and emergency repairs [93].

According to the Digest of UK Energy Statistics (DUKES), in 2017 the use of LPG amounted to 0.37 million tonnes in industry, 0.2 million tonnes and 0.35 million tonnes in the residential and commercial sectors respectively, 0.09 million tonnes in agriculture and 0.07 million tonnes in road transport (autogas) [2].

[25] Around 171,000 British homes are using LPG boilers to heat their homes [35].

Renewable Transport Fuel Certificates (RTFCs) can be issued for supplying bioLPG to road vehicles and non-road mobile machineries (mainly forklift trucks), making those particularly attractive outlets. Indeed, Calor, who is a major supplier of LPG and purchases all the bioLPG produced by Neste, earns RTFCs for supplying bioLPG to forklift trucks [94]. However, this fact does not prevent Calor from offering bioLPG to off-gas grid homes, despite the relatively low bioLPG quantities that are commercially available (40,000 tonnes) compared to the size of the markets which can be rewarded with RTFCs[26].

4.4.1 Arisings and availability

An overview of the main technologies being used or developed across the world to produce bioLPG is presented in Figure 18. While bioLPG is a primary product for some of the processes illustrated, for most of them bioLPG is considered as a co-product alongside other biofuels. A detailed critical discussion of these processes is given in Johnson (2019) [95].

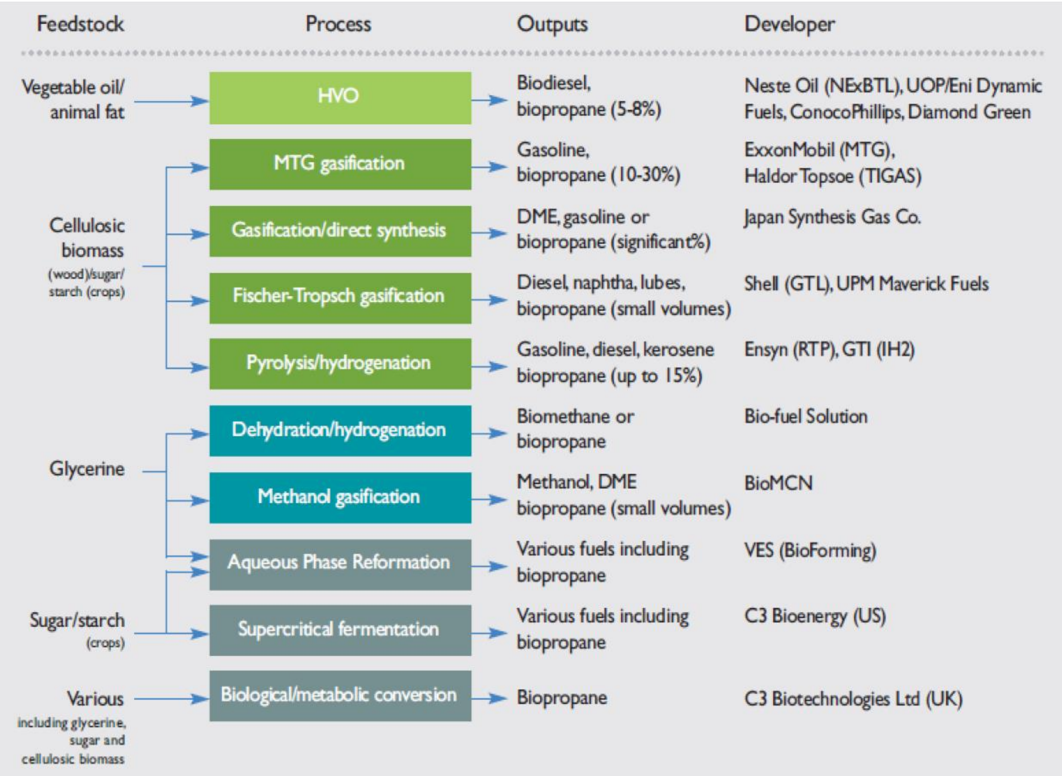


Figure 18: Main technologies being used or developed to produce BioLPG. Source: UKLPG.

A number of UK LPG suppliers are investing in research and development in the procurement of bioLPG from new sources. In addition to the routes given in Figure 18, new UK research has demonstrated a potential microbial synthetic pathway for biopropane production via fermentation [96]. However, of all these processes, only the hydrotreated vegetable oil (HVO), which involves the hydrogenation of vegetable oils or animal fats to produce renewable diesel, is currently commercialised.

[26] The UK market for LPG, as a vehicle fuel for Fork lift trucks is around 75,000 tonnes per year [145].

In 2016, there were fourteen facilities in operation with total biodiesel production capacity of 4.7 million tonnes worldwide; 2.7 million tonnes of which is installed in Europe [97]. For every 100 tonnes of HVO diesel produced, around 5 tonnes of biopropane rich off gases are produced [98]. However, based on the above yield, while HVO biopropane capacity from these fourteen facilities is around 237,000 tonnes, only Neste's plant in Rotterdam currently recovers pure biopropane from the off-gases, producing around 40,000 tonnes of biopropane per year [99], which is chemically identical to conventional LPG and suitable for LPG boilers. It should be noted that with the exception of Neste, which owns four HVO plants, all other plants were not operating at capacity in 2016, so the actual production of biopropane was lower than its maximum theoretical potential [97]. Nevertheless, the use of the majority of the capacity is a realistic scenario as HVO units, due to relatively high CAPEX costs, need to use all the production possibilities of the plant in order to be profitable.

Currently there are no existing or planned HVO units in the UK which means that, in the short term, the only source of HVO bioLPG would be through imports. However, significant investments are being made in HVO plants both in Europe and worldwide due to the drop-in nature of the fuel. HVO production capacity in the EU has increased from 1.7 billion litres in 2011 to 5.0 billion litres in 2018 [48], which is expected to triple by 2025 with an average compound annual growth rate of 10% [100]. In addition, alternative bioLPG pathways are currently being investigated which might deliver a high potential in the future. For example, the University of Manchester, with financial aid from UK Government, is undertaking research on the fermentation of a variety of feedstocks, including waste, for the production of biopropane [93].

Recent work by Atlantic Consulting [101] reported that the global production of BioLPG increased by some 50% between 2014 and 2018; to 200,000 tonnes. Dependent on a number of factors, the authors estimate that this could rise to 300,000 tonnes in 2022, and Europe could be self-sufficient in renewable LPG by 2050 [102]. In order to increase fuel availability, it is possible to blend BioLPG with bio-dimethyl ether (BioDME) and bio-isobutene, which have similar properties [92]. Worldwide production of DME is approximately 5 million tonnes per year [103], with mature well demonstrated conversion technologies. BioDME is a by-product of biomethanol production and UK consumption of biomethanol has been steadily increasing in recent years; with 64 million litres being consumed in the UK between April 2017 to April 2018 [72]. Consumption remains, however, very low in comparison to biodiesel and bioethanol, accounting for just 4% of RTFO biofuels. BioDME is produced through gasification of various feedstocks, including biomass, organic wastes and black liquor. The fuel standard ISO 16861:2015 was published in May 2015 which covers DME for use as a transport fuel or heating fuel. BioDME is a gas at ambient temperature but is relatively easily liquefied at low pressure, similar to BioLPG. Up to 20% BioDME could be blended with BioLPG with no modifications needed to the boiler or fuel storage and handling system. Blends above 20% may lead to corrosion of fuel lines and require further adaptations.

4.4.2 Economics

An investment in a biopropane separation and purification facility at an existing HVO biodiesel plant will be financially attractive only if the price of biopropane at the plant gate is above the price of off-gases, which are typically sent to energy from waste processes, and high enough to offset the capital and operational cost of bioLPG production[27]. However, HVO bioLPG deployment mainly depends on the competitiveness of HVO diesel, which is the primary product of the HVO process, compared to its fossil-based alternative. This means that regardless of the biopropane/LPG price ratio, if the HVO diesel is not competitive then investments in the HVO process will not be justified, which would limit the availability of biopropane [23].

According to Energy and Utilities Alliance (EUA) [35], biopropane costs 8.4p/kWh while the average cost of LPG was around 6.9p/kWh in 2016, which would result in an additional cost of 1.5p/kWh for energy users. Furthermore, evidence obtained from one supplier suggests the premium for bioLPG versus conventional LPG is estimated to be €0.013 per kWh (approx. 1.1 p/kWh) regardless of supply type (i.e. bulk or cylinder) [104]. By streamlining and diversifying production processes, industry estimates that BioLPG could be produced cost competitively with fossil LPG without subsidy by 2030 (approx. £400 per tonne) [92]. A number of suppliers have invested in research & development in this area and are beginning to open up new supply chains, although some claim that support mechanisms are required to encourage and accelerate innovation in order to bring down costs.

4.4.3 Emissions

According to the RHI Evidence Report for biopropane for grid injection [23], the carbon footprint of bioLPG can range substantially from 36 to 180 g of CO_2 equivalent per kWh, with the key variable being the feedstock used to produce HVO biodiesel. Feedstocks such as tallow and waste oils, generate the lowest-footprint biopropane, while higher-footprint feedstocks such as rapeseed or soybean oil generate higher-footprint biopropane. Moreover, a study conducted by Johnson (2017) [105] revealed that the carbon footprint of HVO biopropane varies considerably, to as high as 367 g CO_2e/kWh, depending on the feedstock used to produce HVO biodiesel, the carbon footprint method applied (e.g. allocation method) and other variables. More recently, Atlantic Consulting [101] found that GHG emission factors could be as low as 18 kg CO_2e/MWh.

It is noteworthy that the use of 100% bioLPG fuel or even a semi-renewable blend could result in significant overall carbon savings compared to a heating oil system. According to Johnson (2012), residential heating systems fuelled by conventional LPG are 20% lower carbon than those fuelled by heating oil [20]. In addition, industry feedback has suggested that the use of bioLPG blends can achieve GHG emissions savings of 15-32%[28] compared with conventional LPG. This suggests that replacing kerosene boilers with LPG/bioLPG boilers can reduce the carbon footprint of residential heating systems considerably [106].

The air pollutant emissions from BioLPG combustion are expected to be the same as for fossil LPG, given the fuels have identical properties. The emission factors for LPG used in the NAEI are discussed in section 1.1.3. In a response to the BEIS Call for Evidence on *A Future Framework for Heat in Buildings*, Atlantic Consulting [107] presented the following emission factors for particulate matter (PM) and NOx.

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[27] According to Neste, the investment cost of the bio-LPG separation and purification plant in Rotterdam, with a production capacity of 40,000 tonnes, was 60 million Euros [146].

[28] 32% savings on carbon emissions are achievable at an allocation of 40% BioLPG and 60% conventional LPG.

Table 10. Emission factors for PM and NOx from LPG, natural gas and gasoil combustion. Source: Atlantic Consulting [107].

Fuel	PM (g/MWh)	NOx (g/MWh)
LPG	0.14	81
Natural gas	0.14	116
Gasoil	0.36	122

4.5 Pyrolysis Oil

Pyrolysis oil or bio-oil is a complex dark brown acidic liquid containing hundreds of chemical compounds and is produced by the rapid heating of a feedstock and subsequent condensing of the vapours. A range of different feedstocks have been trialled including lignocellulosic biomass, waste plastics and used car tyres. The European Union regulation EC 1907/2006 established the chemical registration and classification system known as REACH (Registration, Evaluation and Authorisation of Chemicals). Under REACH, Fast Pyrolysis Bio-Oil (FPBO) is defined as "Liquid condensate recovered by thermal treatment of lignocellulosic biomass, at short hot vapour residence time (typically less than about 10 seconds) typically at between 450 - 600°C at near atmospheric pressure or below, in the absence of oxygen". Pyrolysis also produces char, which has a variety of potential uses including as a fertiliser or soil improver.

Crude bio-oil contains water, tars, acids and suspended solids. As a result of this and other fuel properties shown in Appendix B, there are limited applications for untreated FPBO [108]. Fuel properties may be improved by catalytic hydrotreating, which lowers the fuel oxygen content and polarity. Hydrotreated pyrolysis oils may then be co-processed in existing refineries into LPG, kerosene and other hydrocarbons [109]. This will also improve the fuel storage stability, which has been an issue for untreated FPBO [110].

Despite some claims of pyrolysis oil being stored for periods of over one year without substantial degradation, there are a number of unique issues relating to the storage of this fuel. According to BS EN 16900, FPBO should be stored for a maximum of six months, during which time it should be heated to between 15°C and 20°C and constantly agitated in order to avoid phase separation, stratification and settling of solids. The viscosity may increase over time from 40 cSt to 90 cSt at 20°C. The fuel may also be pre-heated to as high as 60-80°C to lower the viscosity before the burner. Transportation issues relating to pyrolysis oil mostly concern the longevity of fuel quality, rather than hazards. It is not considered to be toxic or environmentally hazardous and has a flash point below 35°C, meaning it is therefore not considered a flammable liquid.

Bio-oil obtained from pyrolysis is showing potential as a domestic heating fuel, but research is still ongoing into its suitability and specific characteristics. It is of variable quality due to the varying feedstocks used. The standard ASTM D7544 gives specifications which differentiate between two grades of pyrolysis oil, namely: Grade D and Grade G. Grade D pyrolysis oil is intended for use in residential and small commercial boilers, which require lower solids and ash content, while Grade G is suitable for industrial burners [111]. It should be noted that the Grade D pyrolysis liquid is not intended to be used in residential heating applications unless the boiler is modified to handle this type of fuel [112].

Interesting applications for pyrolysis oil include heat and power, automotive fuels and biorefineries (bio-based chemicals). At the moment, these are in varying stages of development, with only heat and power having been demonstrated at the commercial scale. With regards to the transport fuel market, the properties of thermally produced pyrolysis oil are very different from conventional petroleum derived fuels and therefore bio-oil requires significant upgrading before it can be used as automotive fuels. Currently the efficient utilisation of bio-oil as a transport fuel has not been achieved on a substantial scale, due to its undesirable characteristics, chemical complexity, and instability[29].

Thus, to date, fast-pyrolysis plants have been used to supply renewable fuels for industrial combustion purposes, which is a lower value market compared to transport fuels, but no bio-oil upgrade is required. The domestic heating market can become attractive for bio-oil suppliers, if residential boilers that can handle that fuel are developed.

4.5.1 Arisings and availability

Currently, few fast-pyrolysis plants[30] are commercially available while no industrial sized fast-pyrolysis plants are in operation in the UK, which leads to limited pyrolysis oil being available on the market. Table 11 presents details of industrial sized, fast-pyrolysis oil plants operating globally.

Table 11: Industrial sized fast-pyrolysis plants worldwide [113]

Company	Country	Technology	Feeding Capacity	Bio-oil Capacity	Commissioned
BTG-BTL / EMPYRO	Netherlands	Rotating cone	5,000 (Kg/h)	3,250 (Kg/h)	2014
Fortum – VALMET	Finland	Fluid bed / riser	10,000 (Kg/h)	-	2013
AE Cote-Nord Bioenergy / Ensyn	Canada	Fluid bed / riser	9,000 (Kg/h)	6,400 (Kg/h)	2017
Red Arrows – Ensyn	Canada	Fluid bed / riser	1,667 (Kg/h)	-	1996
Ensyn	Canada	Fluid bed / riser	3,500 (Kg/h)	-	2015
Genting	Malaysia	Rotating cone	2,000 (Kg/h)	-	2005
KiOR	USA	Catalytic fast pyrolysis	21,000 (Kg/h)	-	2014

4.5.2 Economics

According to Bauler (2017), pyrolysis technologies can be economically meaningful when oil prices are over \$60 per barrel. Bio-oil is at a competitive price compared with fuel oil in many markets. For example, the price of Canadian pyrolysis oil (\$13 per GJ), delivered to Rotterdam in 2014, was

[29] Processes for the catalytic fast-pyrolysis, is an area currently receiving significant research and development interest. This processing route targets an upgraded bio-oil, suitable for processing into final fuel products in centralised biorefineries or for co-processing in existing petroleum refineries [116].

[30] This analysis considers the availability of bio-oil (pyrolysis oil), which can be used in residential heating applications. Therefore, this study focuses on fast pyrolysis process as its main product is pyrolysis oil (bio-oil) in contrast to slow pyrolysis, the main product of which is biochar.

comparable to that of heating oil in most markets ($2 per gallon) without any environmental credits [114].

Commercialisation of pyrolysis technologies highly depends on production costs and the competitiveness of the end products against conventional fossil sources. Table 12 presents reported production costs of liquid fuels produced by pyrolysis. Life cycle production costs of liquid fuels produced by pyrolysis vary considerably because of the range of costs related to feedstock type, product yield, plant capacity, technology type[31], value of the final product, life span of plants and discount rates [115].

The feedstock costs presented in Table 12 range from 50 to 97 $/t and contribute about 30-54% to the overall production cost of bio-oil and its derivatives (drop-in liquid fuels). These costs vary, depending on how the feedstock is sourced, collected and processed, and how far it is transported. In addition, according to another study (Perkins et al. 2018), the estimated delivered feedstock prices (on a dry basis) are typically in the range of 70–100 $/ton and include the logistics handling charges and capital and operating costs of drying and grinding the biomass down to a size of 2–6mm [116].

Transportation costs of feedstock can have a significant effect on production costs of bio-oil and other liquid fuels and for a fast-pyrolysis unit to achieve profitability, they should not exceed 64 $/t [115].

Table 12: Indicative production costs of bio-oil and its derivatives [115]

Feedstock Type	Plant Capacity	Feedstock Cost	Product Yield	Technology	Products	Cost
Corn Stover	2000 t/d	83 $/t	152 L/DT	Fludized Bed – FISHER Tropsch synthesis, bio-oil gasification	Fuel	1.48 $/L
Corn Stover	2000 t/d	83 $/t	328 L/DT	Fluidized bed, hydroprocessing	Fuel	0.68 $/L
Corn Stover	2000 t/d	83 $/t	-	Fluidized bed	Bio-oil	0.23 $/L
Wood (Poplar)	2000 t/d	96.57 $/t	222 L/DT	Circulated fluidized bed	Fuel	0.9-0.97 $/L
Hybrid poplar	250-3600 t/d	-	-	Circulated fluidized bed	Fuel	0.61-0.97 $/L
Hybrid poplar	2000 t/d	50.70 $/t	365 L/DT	Circulated fluidized bed	Fuel	0.46-0.54 $/L

Higher profitability can be achieved by increasing scale of production. However, there is a trade-off, between the scale of production and transportation costs. Large-scale facilities should be near the feedstock source to ensure cost-effectiveness, as biomass logistics have a major effect on production costs. In some cases, mobile and smaller scale pyrolysis units can be more profitable. Mobile pyrolysis

[31] Fast pyrolysis is more profitable than slow pyrolysis, because of the higher bio-oil production, which is a higher value product compared to biochar.

units can deal with costs associated with logistics, as pyrolysis products are easier to store, handle, and transport compared to raw biomass [115].

Regarding the investment costs of pyrolysis plants, the Empyro commercial demonstration plant, which processes 120 tonnes per day of biomass, cost around $26 million (in 2014 USD) [116] while Fortum-VALMET, the first commercial pyrolysis plant in Finland, cost about $32 million in 2013 [117].

According to Bauer (2017), the price of bio-oil is comparable to that of industrial wood chips on an energy per dollar basis and bio-oil has a clear advantage in ease of handling and reduced storage costs [114]. To enter that market, bio-oil does not require upgrading to drop-in fuels, but the specifications of ASTM must be met. Further research is evidently required to assess the economic suitability and stability should suitable technology become available in the future.

4.5.3 Emissions

The Residue2Heat project has calculated the potential emission reductions of pyrolysis oil used for residential heating derived from a number of feedstocks, according to the RED methodology. Pyrolysis oil for domestic heating derived from forest residues offers an 89% reduction, from bark and arboricultural arisings 94%, from straw 90%, and from miscanthus 80%; the latter being somewhat lower due to the use of artificial fertilisers in cultivation.

The lifecycle GHG emissions from the combustion of pyrolysis oil were also calculated as part of the Residue2Heat project [37] and ranged from 33 kg CO_2e/MWh for straw and 48 kg CO_2e/MWh for miscanthus.

As shown in Appendix B, FBPO may have a high nitrogen content compared to conventional fuels. Although this is dependent on the choice of feedstock, NOx emissions could be significantly increased compared with kerosene or gasoil [118]. Feedstocks which produce FPBO with high water and solids content, as well as high viscosity, may also lead to higher particulate emissions than fuel oil [108]. However, filtering can greatly reduce PM emissions through the removal of fine chars suspended in the FPBO [119]. A 2012 review of the air quality impacts of FPBO [120] concluded that emissions are likely to be higher than lighter oils such as gasoil and kerosene, more similar to emissions from heavy fuel oil combustion.

4.6 Innovation and future fuels

This section includes brief details of innovative fuels that are not currently feasible for domestic off-gas heating but may prove to be feasible in the future, given technology scale-up and demonstrable feedstock availability. The availability of advanced biofuels in the UK to 2030 was assessed by E4tech (2017) [121]. It found that the technology readiness levels of most advanced biofuels are still at the pilot or demonstration scale with a small number beginning to reach commercial scale, as shown in Figure 19.

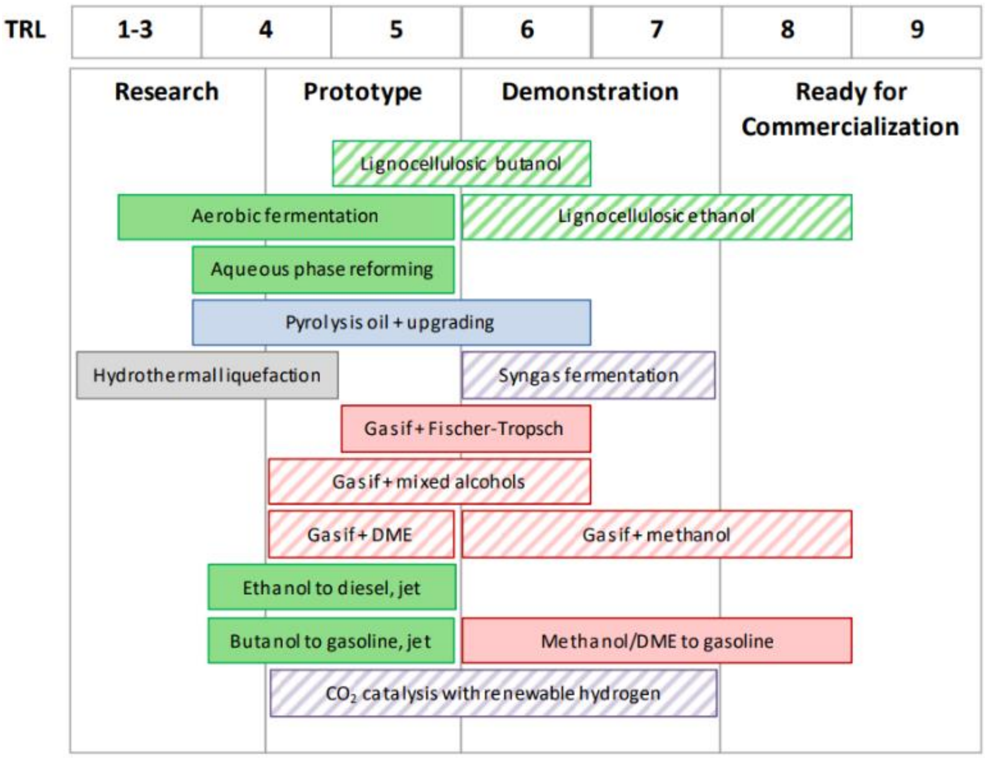

Figure 19. Technology Readiness Levels for advanced bioliquid technologies in 2017. Source: E4tech [121]

4.6.1 Gas-to-liquid (GtL) and E-fuels

The gasification of biomass yields syngas, mostly carbon monoxide and hydrogen, which may be synthesised into renewable bioliquid fuels via several catalytic routes. Processes such as Fischer-Tropsch (FT) synthesis have the key advantage that the hydrocarbon fuels they create are chemically similar to fossil fuel alternatives and can therefore be used as a drop-in replacement. This technology is well demonstrated through research and development, and a number of pilot plants have been developed aiming to scale up the process to commercial level.

Global production capacity of FT liquids is estimated to be 354 million litres per year [121], although many pilot and demonstration plants are not yet producing fuel commercially. Global production capacity of FT bioliquids may surpass 1.3 billion litres per year by 2030 based on E4tech maximum projections [121], but UK capacity will be limited until 2026. In its recent report *Biomass in a Low-Carbon Economy* [122], the Committee on Climate Change stated that bioliquids in niche markets (such as the off-gas grid heating sector) could provide a route to develop gasification technologies which are proving slow to commercialise.

Additionally, as shown in Figure 18, a significant by-product of gasification and fuel synthesis is biopropane which may be produced in larger proportions than in HVO production; the main source of BioLPG today. Therefore, increases in the production of FT fuels led by demand in other sectors may increase the availability of BioLPG for heating.

FT Biokerosene

Perhaps the most relevant advanced bioliquid fuel for the UK off-gas grid heating sector is FT biokerosene. Research and investment in this fuel is driven principally by the aviation sector, but increased production in the future may increase the availability of FT biokerosene for heat. This is particularly true for off-gas grid heating, whereby kerosene demand is highest in the summer for the aviation sector and highest in the winter for the residential sector, as shown in section 1.1.1, Figure 1.

A comprehensive review of biokerosene production, availability and prospects was carried out by Kaltschmitt and Neuling (2018) [123]. The annual rate of growth in air transport is 4.2% per annum in OECD nations and greater than 6.0% per annum in economically developing countries such as India, China and Brazil. In addition, members of the International Air Transport Association have committed to reduce sectoral CO_2 emissions by 50% by 2050 relative to 2005 levels. The combination of large growth rates and emissions targets have created a high demand for low carbon aviation fuels, and renewable kerosene is favoured due its advantageous fuel properties and performance in jet engines. Under a high growth rate scenario, renewable jet fuel consumption in Europe could increase to over 80 million tonnes by 2050 [124]. Key UK stakeholders in this area include Velocys and LanzaTech, the former of which announced in December 2018 it had secured funding from the Department for Transport (DfT) to develop a commercial scale plant to produce kerosene from waste gasification.

The lifecycle GHG emissions for FT biokerosene were estimated at 11-47 kg CO_2e/MWh from the gasification of lignocellulosic biomass [125].

E-fuels

E-fuels, also known as power-to-liquid or PtL fuels, are synthetic liquid hydrocarbons generated from renewable electricity. E-fuels are generated from Fischer-Tropsch synthesis, but the carbon monoxide and hydrogen are sourced from air and water rather than from the gasification of biomass. Hydrogen is produced from the electrolysis of water using renewable electricity and CO is produced from CO_2 via the reverse water-gas shift reaction.

Advantages of E-fuels in Europe include reduced import costs and greater energy independence, as well as reduced land requirements and emissions associated with land-use change. Under multiple scenarios developed by the German Energy Agency (2017), E-fuels are forecast to supply >70% of final energy demand in the EU transport sector by 2050 [126]. The aviation sector is again another key driver in the development of E-fuels and biomass gasification could complement PtL development, rather than acting as a competing technology [127].

Lifecycle GHG emissions for E-fuels are dependent on the electricity mix used to supply process energy, as well as on the source of CO_2. One study estimated GHG emission factors for e-kerosene to be 40-101 kg CO_2e/MWh [128], which includes emissions from the construction of production facilities.

4.6.2 Hydrothermal liquefaction (HTL)

The HTL process uses water at high temperature and pressure to form a dark, viscous, odorous bioliquid known as biocrude. HTL biocrude differs from fast pyrolysis bio-oil (FPBO) in that it has a lower oxygen content, higher viscosity and higher energy content (up to 40 MJ/kg) [129]. Hydrothermal biocrude also has a high acidity which, combined with its high viscosity, will lead to similar issues with fuel storage and handling as discussed for pyrolysis oil in section 4.5 Nevertheless, the HTL process has the key advantage of being able to use high moisture content feedstocks such as algae and wastes, which may be difficult to gasify without a severe energy penalty.

HTL technology has been well demonstrated at the research and pilot scale, although there have been some issues scaling up the process to continuous commercial operation. HTL of lignocellulosic biomass is not as advanced as FPBO, as shown in Figure 19. Key stakeholders in this area include Licella (North Sydney, Australia), one of the largest pilot plant reactors producing HTL biocrude in the world. In contrast to FPBO, at the time of writing there are no known boilers in operation using HTL biocrude. Though this is technically possible, there are no fuel standards as there are for FPBO.

The undesirable fuel properties of HTL biocrude have the potential to be improved through hydrotreating, upgrading and refining into drop-in fuels, but this is not currently being done at the commercial scale. Tzanetis et al. (2017) [130] demonstrated that HTL biocrude may be upgraded into biokerosene with lifecycle GHG emissions of 47 kg CO_2e/MWh, although production costs were approximately twice that of traditional fossil aviation kerosene.

4.6.3 Bioethanol for supplementary heating

Recently there has been a growing demand for bioethanol stoves and fireplaces in both the UK and globally. These appliances are typically rated at <5 kW and hence provide a small amount of supplementary space heating to properties in the residential and commercial sectors, although they are classed as more of decorative feature and are most popular with high-end residential developments and in the hospitality sector. The growing demand for these appliances is thought to be due to the following benefits in comparison to electric fires or solid fuel stoves:

- Generation of a real flame
- Aesthetically pleasing
- Do not require a flue or installation
- Do not impact on air quality
- Relatively low cost
- Can be fully automated and controlled from a smartphone
- No mess or ash
- “Eco-friendly” fuel

A large market driver for bioethanol fires is thought to be the concerns over emissions from solid fuel stoves burning wood and coal. As a result of the low emissions, appliances may be installed without a flue which reduces the thermal losses which can be high in wood burning stoves. Despite this, studies have shown that bioethanol fireplaces can detrimentally affect indoor air quality [131].

Safety concerns have also been raised by a number of authors over the risk of accidental burns [132] and as a result, a new European standard was developed, BS EN 16647:2015. Most manufacturers now accredit their appliances to BS EN 16647 and key stakeholders in this area include Ecosmart, Planika, Imagin Fires and Ebios. The cost of bioethanol fires varies significantly, with smaller appliances available from large DIY stores costing as little as £80 and more bespoke appliances costing £2000 or more. Fuel is supplied in 2-5 litre containers and is widely available to the public, costing on average £5-6 per litre. There is very limited market information available on the number of bioethanol fireplaces sold each year in the UK, but it is known to be a rapidly growing area.

5 Practical Constraints of Installation

Due to the range of options being considered in relation to the use of bioliquids in the existing housing stock, a field-based survey of existing oil-fired properties was undertaken to validate findings from the literature review and stakeholder discussions, and to fill some knowledge gaps relating to installation costs and practical constraints.

The works required and the costs associated with installing a new bioliquid heating system or modifying an existing oil boiler so it can operate on a B30K blend have been assessed. As BioLPG is a drop-in fuel for existing LPG-fired systems and does not require system modification it has not been included in this exercise.

The survey evaluated four properties that represented the likely range of situations, covering detached, semi-detached and terraced properties. A detailed inspection of the existing oil-fired heating system and its components was undertaken to evaluate:

- Basic property type
- Existing fuel tank (type/location/age)
- Existing oil boiler (type/location/age)
- Works, skills and expertise required to remove the existing equipment
- Estimated cost of removal

The survey was augmented with the application of professional judgment concerning issues around the scope of works required and by reference to existing industry standard costs for parts, equipment and labour. This enabled six scenarios that will be faced by consumers considering switching to bioliquids to be costed:

- Full replacement of the oil tank and the oil boiler; or
    - Replacement of the oil boiler only
    - Replacement of the oil tank and oil feed pipes only
- Modification of oil tank and oil feed and oil boiler to operate on a B30K blend; or
    - Modification of the oil tank and oil feed pipes only to operate on a B30K blend
    - Modification of the oil boiler only to operate on a B30K blend

This information, although representing a small sample size, has been used to validate evidence and consolidate figures for use in the modelling exercise; a summary of the findings is presented below.

5.1 Installation requirements

Based on the age and type of existing boiler systems, two thirds of installed oil boilers are not suited to using bioliquids or blends without modification. Further explanation for this assumption is given in section 6.2 . This means that for most off-gas grid consumers to be able to use bioliquids, their choice will be limited to either a modification of the existing system to use a blend up to 30% (see section 3.1 or a full replacement of their oil-fired system. In these circumstances the new system could be designed to operate on a B30K blend or any other blend or type of bioliquid, although the boiler would need to be optimised to a given blend percentage by a qualified heating engineer.

Given the diversity of the off-gas grid housing stock and the variation in heating system type and age, the issues faced in any given property will be bespoke. It is possible that some consumers will seek to retain their old fossil fuel system, however this is thought to be mostly unlikely as there would not be space for two systems in most domestic situations. In addition, the costs and complications of retaining the fossil fuel system as back-up are significant and will lead most consumers to remove the old system.

Particular costs and challenges that have been identified in relation to specific installation components and related activities are presented and discussed below.

Basic property type

The costs, constraints and scope of work required to remove the existing system and install a replacement were broadly similar irrespective of the archetype. In practice, costs are associated with ease of access, working space, the particular spatial arrangements of the system and the exact locations of the fuel tank and oil boiler.

Removal of existing fuel tank

For a full-system replacement, the removal of the existing fuel tank will be a reasonably intrusive and expensive operation; it requires an OFTEC qualified engineer and a waste licence carrier for safe disposal. Specialist equipment may be required such as lifting and carrying equipment (e.g. fork-lift, front-end loader) to assist with removal.

The tanks in the survey ranged in size from 2,000 to 2,500 litres and varied in age from 8 to 18 years. Typically, the removal of the oil tank can be completed in an estimated 1 to 1.5 days. Below are the estimated costs of removal and disposal of the fuel tank at each property in our survey:

Table 13. Estimated costs of the removal of the fuel tank

Site	Estimated cost of removal of fuel tank
Detached property	£1,100
Semi-Detached - property 1	£1,100
Semi-Detached - property 2	£950
Terraced property	£950

Removal of existing oil boiler

None of the properties in our survey had boilers located in positions that prevented their easy removal. The boilers were between 2 and 7 years old. The boilers rated output ranged from 15kW to 36kW, with an average output of 28kW.

The works to remove the oil boiler require an electrician and a heating engineer. The expertise required to undertake these tasks is not specialist and is widely available from the current domestic heating sector. Typically, the removal of the oil boiler can be completed in 0.5 days.

Table 14. Estimated costs of the removal of the oil boiler

Site	Estimated cost of removal of oil boiler
Detached property	£280
Semi-Detached – property 1	£280
Semi-Detached – property 2	£370
Terraced property	£370

Based on the above, the average cost of all removal works per property, irrespective of archetype, is ~£1,350. This excludes the costs of the supply and installation of a new bioliquid boiler and replacement tank.

In two of the properties surveyed an AGA provides space heating for the kitchen. Based upon experience and understanding of the domestic heating market it is thought that a significant number of oil-fired off-gas grid detached properties will contain an AGA. These are generally fuelled from the oil tank and cannot be operated on bioliquid without the addition of additives. Consumers are likely to be reluctant to switch to bioliquid if it would potentially compromise the functionality of their AGA. This could greatly reduce the appeal of conversion for a number of the off-gas grid properties. Further work is required to evaluate this constraint.

Installation of replacement boiler

The costs of installing a new heating system are made up of labour and equipment costs. Equipment costs presented below include mechanical and electrical works such as boiler control systems, electrical wiring and piping. Based upon the field survey, it is estimated that the average labour cost *of installing* a new bioliquid boiler will be around £700 per property, irrespective of archetype.

The likely cost of a new bioliquid boiler will depend on the size of the boiler, type of bioliquid it is designed to operate with and whether it feeds a hot water storage cylinder or provides instant direct hot water. The basic components and design of a bioliquid boiler will be very similar to domestic oil boilers and it is therefore reasonable to assume that bioliquid boilers and their parts can be produced at similar production costs to oil boilers, but with a premium due to smaller production volumes.

As such products are not commercially available, the price premium is unknown. However, based on professional judgement, the findings from the literature review and feedback from stakeholders involved in the domestic fossil-fuel installation market; considering the material types and additional components required, a 25% uplift has been assumed to be reflective of the longer-term situation once economies of scale are achieved. In the meantime, the premium for the boiler may be higher.

Table 15. Possible cost of a new bioliquid boiler capable of using any form of bioliquid

Boiler	Estimated supply cost of oil boiler	Estimated supply cost of bioliquid boiler @ plus 25%
Estimated cost of oil boiler (low)	£1,100	£1,375
Estimated cost of oil boiler (mid)	£1,650	£2,065
Estimated cost of oil boiler (high)	£2,200	£2,750

Based on this analysis, it can be concluded that a new bioliquid boiler will have a central (mid) supply cost of £2,000, with ~£700 of installation costs on top.

Installation of replacement tank

Stakeholders have reported that the installed cost of a new bioliquid tank will vary from £1,000 to £2,000 depending on site requirements. Based upon the survey and experience of the domestic heating market it is understood that the foundations in place for the old oil tank may not be adequate. Older oil tanks are often fixed to brick piers for example and that would not be considered suitable for a new tank, and many properties may lack current standards in terms of fire protection. The distance of fuel feed pipes and associated costs must also be accounted for. It is considered that ~£500 should be added to the basic tank supply cost to account for these issues. However, it should be noted that these issues and resultant costs would also likely arise when the existing tank came to the end of its life and required replacement on a like-for-like basis, even if the same fuel type was still to be used.

Based on this analysis, it can be concluded that supplying and fitting a new bioliquid tank will have a central (mid) cost of ~£1,900.

5.2 Cost scenarios

Based on this small survey, the cost of fitting a new bioliquid system (capable of using any form of bioliquid) in a typical off-gas grid property in any archetype will be ~£5,950, comprising:

- Removal works for both the oil boiler and tank, irrespective of archetype: £1,350
- Installation of a new bioliquid boiler, central (mid) cost: £2,700
- Installation of a new bioliquid tank, central (mid) cost: £1,900

As described in earlier sections, the system requirements vary dependent on the age and type of the existing system, and the replacement fuel type. Around a third of existing oil-fired properties are assumed to be capable of using a blend and under these circumstances the existing system would be modified and does not need to be fully replaced. For the other two thirds of properties there will be a range of options for modifications and system replacements depending upon the age and design of the existing oil boiler and oil tank; the range of costs for these scenarios is shown below.

Table 16. Costs of scenarios that face consumers

Scenarios	Description	Likely cost
Full replacement of the oil tank and the oil boiler	Both the existing oil boiler and tank are incompatible with bioliquids and therefore a full-system replacement is required. A dedicated bioliquid boiler would be installed that would likely then be compatible with blended fuels, although an engineer would be required to optimise the system for the selected fuel option.	£5,950
Replacement of the oil boiler only	The oil boiler is ageing or incompatible, but the existing tank has recently been replaced and is compatible with the new fuel type. A dedicated bioliquid boiler would be installed that would likely	£3,025

	then also be compatible with blended fuels, although an engineer would be required to optimise the system for the selected fuel option.	
Replacement of the oil tank and oil feed pipes only	The existing oil boiler has recently been installed (within 3-5 years) but the oil tank is ageing or incompatible with the new fuel type and need to be replaced. The modified system would be compatible with blends up to B30K. A new burner head is likely to be required for the existing boiler that costs £350 fitted.	£2,925
Modification of oil tank and oil feed and oil boiler	The existing oil boiler and tank have recently been installed (within 3-5 years) and are compatible with the new fuel type. A new burner head is required that costs £350 fitted and the existing fuel tank is cleaned and flushed at a cost of £450. Some older parts or weaker components of the system may require replacement and a contingency of £200 has been allowed. The modified system would be compatible with blends up to B30K.	£1,000
Modification of the oil tank and oil feed pipes only	The existing oil boiler has recently been installed (within 3-5 years) and is compatible with the new fuel type. The existing fuel tank is cleaned and flushed at a cost of £450. Some older parts or weaker components of the system may require replacement and a contingency of £200 has been allowed. The modified system would be compatible with blends up to B30K.	£650
Modification of the oil boiler only	The existing oil boiler and tank have recently been installed (within 3-5 years) and are compatible with the new fuel type. All tank components are compatible and therefore no tank modification is required. A new burner head is required for the boiler that costs £350 fitted. The modified system would be compatible with blends up to B30K.	£350

5.3 Key findings

- The archetype had little influence on the issues and costs of conversion; they were similar irrespective of whether the property was terraced, semi-detached or detached.
- The existence of an AGA in the kitchen is a potentially significant barrier to conversion as this is usually connected to the oil tank and cannot operate on bioliquid without modifications.
- In all properties the age and condition of the oil boiler was different from the age and condition of the oil tank[32], meaning that the works to replace or upgrade the system at each property may not always include both the tank and oil boiler.
- The costs faced by consumers will be highly site specific and depend upon whether system must be replaced in full, in part or modified to use a B30K blend.

[32] Whilst a much larger survey would be required, it can be tentatively inferred that the ages of existing systems varies between the oil tank and oil boiler. Based upon this small sample survey the oil tank will often be older than 10 years, whereas the boiler is usually less than 10 years in age.

6 Discussion

There are evidently a number of options, both now and in the future, for bioliquids to meet the needs of the off-gas grid heating sector in the UK. This section discusses different deployment scenarios to illustrate the potential costs, emissions and resource constraints, then presents the high-level findings from the modelling work and a brief constraints analysis.

The deployment model considers uptake of bioliquids heating to 2050, with the ability to switch between the growth scenarios presented in section 2.3 .

6.1 Scale of the opportunity

There are over 1.5 million rural off-gas grid properties in England and Wales, heavily dominated by oil-fired heating systems. Electric heating systems, installed in just over 300 thousand properties were excluded from the scope of this analysis, as they are unlikely to switch to bioliquid fuels due to costs and additional infrastructure requirements[33]. The total number of properties under consideration in this analysis is therefore just under 1.17 million, as illustrated in Table 17.

Table 17: Number of off-gas grid properties in the England and Wales, by current fuel type [24]

Number of off-gas grid properties (England & Wales)	Oil	Solid fuel	LPG	TOTAL
Detached, high thermal demand	161,674	15,885	30,919	208,478
Detached, low thermal demand	451,511	22,282	42,943	516,736
Semi-detached, high thermal demand	147,427	28,263	53,249	228,939
Semi-detached, low thermal demand	46,637	2,952	5153	54,742
Terraced, high thermal demand	74,960	20,200	37,789	132,949
Terraced, low thermal demand	28,448	256	1,718	30,422
TOTAL	**910,657**	**89,838**	**171,771**	**1,172,266**

Based on the annual heating demand, appropriate boiler sizes range from 15-40 kW_{th} dependent on property type and thermal demand, as illustrated in Table 18.

Table 18: Typical boiler sizes of UK properties, by archetype

Housing Type	Annual heating demand	Boiler size
	(kWh)	**(kW)**
Detached, high thermal demand	32,500	40
Detached, low thermal demand	16,640	30
Semi-detached, high thermal demand	20,250	30
Semi-detached, low thermal demand	10,140	20
Terraced, high thermal demand	15,600	20
Terraced, low thermal demand	7,540	15

[33] Electric-heating is the subject of a separate BEIS commission.

The total installed heat capacity represented by these properties is 35 GW_{th} with annual heat demand in the region of 23 TWh, as illustrated in Table 19.

Table 19: Total annual heating requirement in England & Wales, by property type

Housing Type	Total installed heat capacity	Total annual heating requirement
	(GW_{th})	(TWh)
Detached, high thermal demand	8.3	6.8
Detached, low thermal demand	15.5	8.6
Semi-detached, high thermal demand	6.9	4.6
Semi-detached, low thermal demand	1.1	0.6
Terraced, high thermal demand	2.7	2.1
Terraced, low thermal demand	0.5	0.2
TOTAL	**34.9**	**22.9**

6.2 Market and technology constraints

Technology availability is likely to constrain the rate of growth in bioliquid boilers, as dedicated component parts, tanks and ancillaries are not yet widely deployed or commercially available at competitive prices in the domestic sector. Despite this, the issues and requirements are fairly well understood, particularly for biodiesel and blends up to B30K where field trials have been conducted and guidance documents are available. The only major constraint on BioLPG is fuel availability and scalability of source processes.

The product lifespan stated in Table 20 refers to the boiler and main heating system, as opposed to the tank and other component parts. This refers to the recommended lifetime of the boiler according to manufacturers – in reality, boiler lifetime may be prolonged for 25 years or more, though this is not recommended. General components such as pipes, seals and filters are typically replaced at regular service intervals, ranging from 1 to 5 years.

A limited amount of data is available on the type and age of boilers currently installed in off-gas grid homes. Some data is available in housing surveys, as shown in Figure 20 for England [133].

Nationally, on average just 37% of domestic hot water is delivered from a regular boiler system with a hot water cylinder. This is due to significant growth in combination boilers in homes using gas. Off-gas grid properties have a much higher prevelance of hot water cylinders; on average the percentage of oil-fired properties with a hot water cylinder is 78% in terraced houses, 86% in semi-detached houses, and 84% in detached houses[34] [133].

[34] Data from the English Housing Survey 2015/16 under a Special Access License.

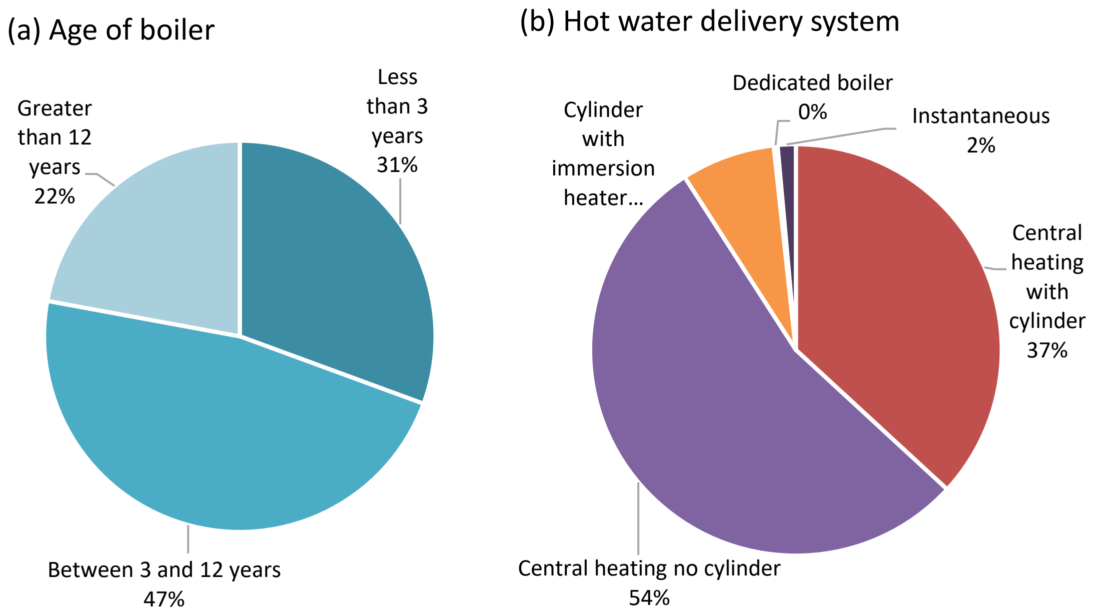

Figure 20. Boiler types and ages in England in 2016/17 according to the English Housing Survey [133].

In this work we assume that 60% of replacements will retain their old boiler system (lowest cost option) and 40% replace their old system with a combination boiler (highest installation costs). In reality there may be several factors why off-gas grid properties may not be suited to combination boilers but this can only be assessed on a case-by-case basis.

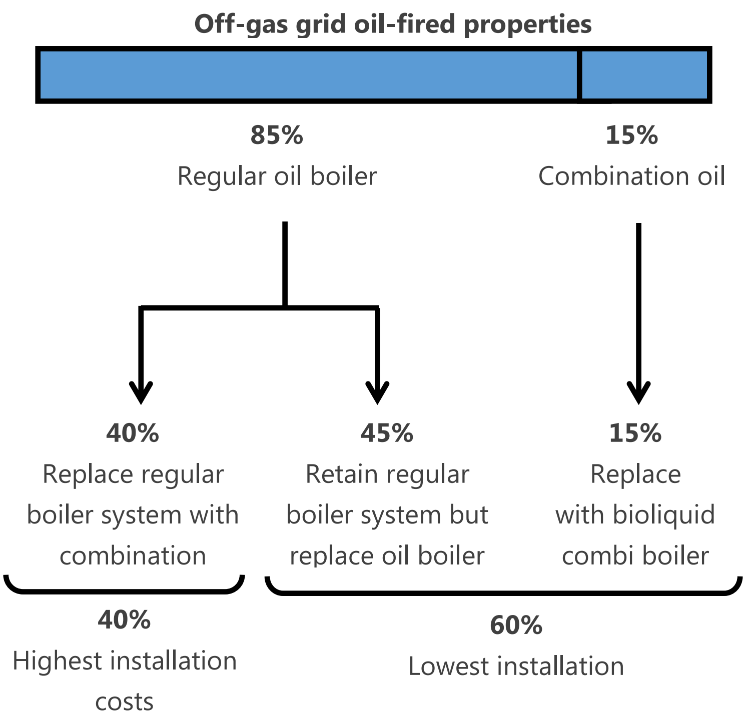

Figure 21. System replacement assumptions, by boiler and system type

The indicative installation costs in Table 20 represent typical values across all housing archetypes, based on findings from the literature review, stakeholder discussions and the field-based survey. It is evident that there is likely to be signficant variation in bioliquid heating system costs; however, many stakeholders have suggested that they may present a cheaper option than heat pumps [134]. It should also be noted that the relationship between total cost and boiler size (kW) is non-linear. Smaller boilers (~20 kW) will have a higher installation cost in £/kW than larger boilers (~40 kW).

Table 20: Technology costs, efficiency and lifespan of fossil- and bioliquid-heating systems

Product Type	Installation cost	Annual maintenance cost (excl. fuel)	Efficiency	Lifespan
	(£/kW)	(£/kW)	(%)	(years)
Oil-fired boiler	117	5	90	15
LPG boiler	98	3	92	15
Bioliquid heating systems:	-	-	-	-
Converted oil-fired boiler (B10K)	117	6	90	15
Converted oil-fired boiler (B30K)	125	7	90	15
Converted oil-fired boiler (B50K)	267	10	90	14
Dedicated biodiesel boiler (B100)	267	18	90	13
Vegetable oil-fired boiler	325	29	88	10
UCO-fired boiler	325	29	88	10
BioLPG boiler	98	3	92	15

The installation cost (£/kW) stated in Table 20 includes all equipment required for the given scenario, as described in section 5, as well as the cost of physical installation and old equipment removal costs, if appropriate. Costs based on a typical installation size of 26kW$_{th}$, and exclude value added tax (VAT).

Based on discussions with stakeholders, the compatibility of recently installed oil boilers, tanks and other components with up to a B30K blend offers an opportunity for rapid conversion of up to a third of the oil-fired housing stock. This would equate to over 250k properties, with an installed capacity of over 8 GW$_{th}$.

The remaining properties, with boilers over 5 years old, would be required to replace the system to accommodate bioliquids. Initially, those installed more than 10 years ago would be coming towards the end of their operational life and potentially operating at lower efficiencies, so would be a cost-effective first target to replace. Beyond these, systems installed between 5 and 10 years ago would also require full replacement, but with more life remaining in the technology and improved efficiencies, the cost-effectiveness becomes more questionable.

Replacing the ageing boilers, as well as converting the most recent systems to run on bioliquids would impact on over 500k properties and would deliver over 16 GW$_{th}$ of renewable heat capacity. If these options were gradually phased in over the next decade, the peak replacement rate would be 30k boilers and tanks per annum, which is similar to the current natural replacement rate.

Delivering such changes in line with the step change growth scenario would lead to the peak replacement rate increasing beyond 50k boilers and tanks per annum, which exceeds current installer capacity and may therefore become constrained.

6.3 Fuel supply constraints

As evident from section 4, globally there is a significant supply of and demand for bioliquids. However, readily established and other emerging markets are competing for the resource which constrains availability for new markets. For example, using the kerosene and biodiesel consumption figures given in earlier sections, for comparison, if all biodiesel currently supported under the RTFO was diverted to heating sector, this still would only cover 31% of heating demand and would have significant impact on fuel prices and wider decarbonisation strategies.

Availability is highly sensitive to market dynamics and pricing, so in the absence of a market and associated supply infrastructure for bioliquids in the UK heating sector, it is difficult to accurately quantify the truly available resource. Fuel prices can vary from month to month; figures in Table 21 represent retail prices in December 2018. Where prices were not available for blended fuels, available figures have been apportioned according to their bioliquid content.

Table 21: Model assumptions of price, availability, and emissions factors for fossil- and bioliquid fuels.

Fuel Type	Fuel price	Net calorific value	Emissions factor	Availability
	(p/kWh)	(GJ/tonne)	(gCO2eq/MJ)	(million litres/year)
Heating oil (Kerosene)	3.8	43.9	72.1	-
LPG (Propane)	6.5	45.9	64.0	-
Solid fuel (coal)	4.2	27.2	105.3	-
B10K	4.1	43.2	65.9	3011
B30K	5.7	41.9	53.4	2520
B50K	5.4	40.5	41.0	2029
B100	7.1	37.2	9.9	802
Vegetable oil	5.7	37.6	7.0	2176
Used cooking oil (UCO)	5.2	35.8	1.8	857
BioLPG	7.3	45.9	34.2	77

In order to achieve the ambition described above, replacing the ageing boilers and converting the most recent systems to run on bioliquids, action would be required to address fuel supply constraints. In the context of this analysis, availability as stated in Table 21 refers to the current supply to the UK (domestic and imported) with no consideration of alternative markets.

Biodiesel supply would evidently be constrained very quickly; however, there is potential to increase the UK supply base in conjunction with a reduction in demand from the road transport fuel sector, which is likely to coincide with the time that demand from the heating sector would become significant (in the period from 2025 to 2030). There is a limit to the cost competitiveness of bioliquids in the heat sector. Given current levels of fuel poverty and the basic human need for warm homes, there is a limit to the price which can or will be paid for heating, whereas this limit may be higher in the vehicle sector where there is more room to manoeuvre with fuel pricing since consumers are used to paying more per kWh of energy for transport than for energy for heating.

Whilst the availability of UCO does not appear to be a constraint to deliver this ambition, this relates to UCO as the fuel-type as opposed to the raw material. However, due to the favouring of waste-derived fuels, the likelihood is that most of the biodiesel would be produced from UCO and therefore availability of UCO as a feedstock is likely to be a major constraint. Additional collection capacity, driven by the announcement in the recent Resource & Waste Strategy that separate food waste collections are to be rolled out more widely across England and Wales may address this to some extent. However, the ability to convert this to biodiesel for distribution to domestic customers is expected to be a challenge.

Another area of concern that has been raised by a number of stakeholders, but has not been investigated in depth is the ability of the fuel supply chain to accommodate a greater range of fuel options. This includes capacity at terminals, storage and distribution depots to receive, store and handle multiple fuel types; as well as capacity of fuel suppliers at local depots and within their delivery fleet to store, handle and deliver a range of fuels.

Furthermore, consumer awareness has been a major issue within the bioenergy and biofuels sectors in recent years, due to the complexity and lack of awareness of the options, impacts and consequences of biomass-derived fuelling options. This issue is likely to prevail with regard to bioliquids, especially if more than one bioliquid-fuel option is available.

6.4 Cost impacts

The costs to the consumer of purchasing and installing a new bioliquid heating system are dependent, not only on the housing archetype, but also on the system being replaced and the scale of works required (as discussed in section 5). For example, the typical boiler type in an older property is a regular system, whereby space heating is provided directly from the boiler and hot water is stored in an insulated tank, accompanied by a header tank. In some cases, the consumer may wish to replace this system with a combi-boiler which provides instant hot water without the need for a tank and may also want to relocate the boiler to a different part of the property. The installation costs of this scenario would be significantly higher than a property that already has a combi-boiler and wishes to retain it in the same location; however, as this is a consumer choice such additional cost has not been accounted for in the analysis. Moreover, in some off-gas grid properties it is not possible to install a combi-boiler due to various practical constraints, so the boiler would be a heat only or system-type boiler.

Typically, the cost of replacing a fossil oil-fired system like-for-like with a bioliquid-fuelled system would be 60-80% more per kW which equates to between £1-3k, depending on the capacity of the boiler and fuel tank required.

The extent and costs of maintenance associated with the general upkeep and also system fault finding and repairs is also likely to be higher for bioliquid boilers. Unlike larger commercial and industrial systems that may have a dedicated system manager on-site to oversee performance and operation, domestic systems may only be serviced or checked during the annual service or when there is a fault in the system. As BioLPG is a drop-in fuel, the costs of installation and maintenance are not expected to change.

According to a 2018 survey by Which?[35], boiler owners will have to pay for a repair on average once every 3.5 years with the repair costing £155-205. Based on discussions with stakeholders, the frequency of repairs could be expected to increase from once every 3.5 years to once every 1.5 years. Common reasons for emergency callouts for gas condensing boilers include blockages in condensate pipes due to ice formation in cold weather. This was especially true of the 2018 'Beast from the East'. For bioliquid systems, extreme cold weather incidents may lead to fuel crystallisation and blockages in fuel supply lines, filters and injectors. Other common failures for B100 systems include injectors and fuel pump seals, which may require more regular replacement at increased cost.

Annual maintenance costs (excl. fuel costs) will typically be 1.5 to 3 times higher for bioliquid fuelled systems, compared with the fossil alternative. Furthermore, fuel costs will be greater, increasing by 10-50% depending on whether the replacement is a blend or dedicated bioliquid fuel. In addition to the fuel costs, increased frequency of deliveries due to the smaller tank sizing may lead to greater delivery costs being incurred by the consumer. This is not the case for bioLPG, as a drop-in fuel the frequency of deliveries will remain unchanged, but the fuel is currently more costly, so up to a 12% increase can be expected, at least until supply increases and uptake becomes more widespread.

On a practical level, there are many factors which will affect the receptiveness of homeowners to bioliquid heating systems, and the scale to which fossil fuel use can be reduced in the off-gas grid sector. In addition to the issues such as fuel cost, conversion cost, technical challenges and maintenance requirements, there are also social considerations.

A major consideration is the impact that any heat policy will have on levels of fuel poverty in the off-gas grid sector, which is already higher than those who have gas central heating. Through a combination of stakeholder interviews and online surveys, we asked fuel suppliers and boiler manufacturers to rate the expected customer receptiveness to bioliquids on a scale of 1 to 10. The responses were very varied, with some respondents predicting a receptiveness of 1 unless there is a tax on standard mineral fuels or a significant incentive to switch. Others predicted a receptiveness as high as 9 for drop-in fuels which do not require major modifications.

Guarantees would need to be in place to ensure that any bioliquid fuel is sustainably sourced, offers genuine GHG savings and meets the fuel specifications for use in boilers. The potential for 'rogue traders' to exploit consumers by selling inferior quality fuel would need to be addressed: this happened some years ago in the transport sector, but incidence has reduced with the implementation of fuel standards such as EN 14214. Using inferior quality fuel in boilers could lead to a number of problems including blocking of nozzles and piping, higher emissions and reduced boiler lifetime. Similarly, guarantees would need to be put in place to ensure that consumers have a suitable tank for the fuel or blend that they are using. The impact of tank ownership (most heating-oil customers) versus tank rental (most LPG customers) on consumers would need to be addressed.

[35] According to a survey of 2,530 Which? Members with boiler cover in May 2018 https://www.which.co.uk/reviews/boiler-cover/article/how-to-choose-the-best-boiler-cover

6.5 Air Quality and Greenhouse Gas impacts

Based on the range of emissions factors stated for each of the prioritised fuels in section 4, full conversion of all suitable off-gas grid housing stock to bioliquids could deliver carbon savings in excess of 6.6 $MtCO_{2eq}$ per annum. However, as discussed above, the constraints on technology and fuel availability are likely to lead to a somewhat more modest conversion/replacement rate.

In line with the opportunities discussed at 6.2 , conversion of the most recently installed systems, replacement of the ageing boiler stock (existing oil and solid fuel boilers), and conversion of at least half of the existing LPG systems to run on BioLPG would deliver savings in excess of 3 $MtCO_{2eq}$ per annum by 2050 and potentially as much as 2 $MtCO_{2eq}$ per annum by 2030, as illustrated below.

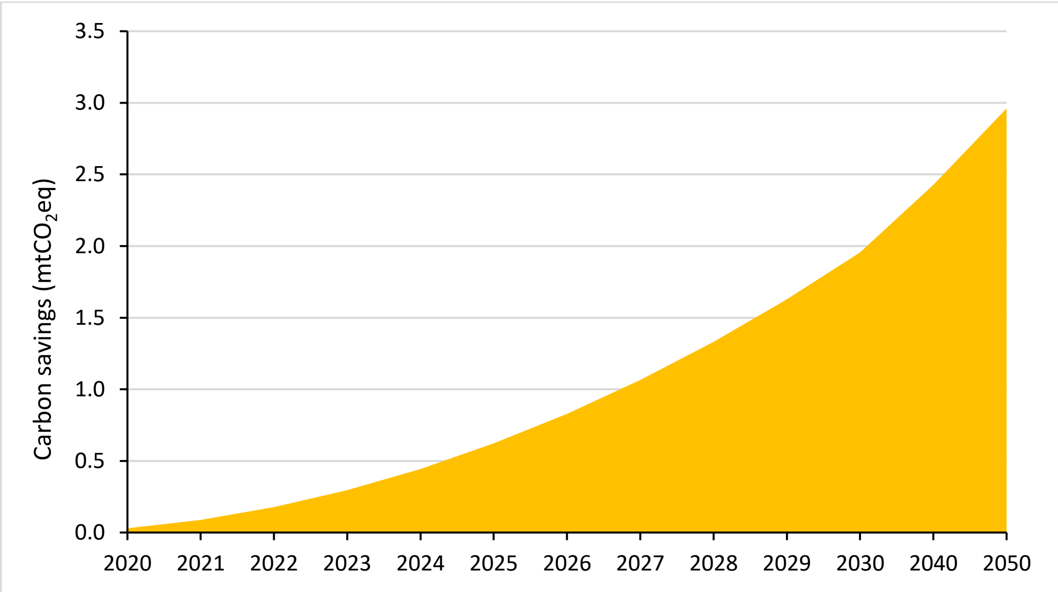

Figure 22: Potential carbon savings achieved by replacing fossil-fuels with bioliquids and bioLPG in the off-gas grid housing stock *(extracted from Deployment Model)*

The air quality impacts of using bioliquids and blends in domestic boilers is highly uncertain due to a lack of sufficient evidence and variable results. The available evidence for emission factors is discussed in detail in sections 1.1.3 for fossil fuels, 4.1.5 for vegetable oils, 4.2.3 for UCO, 4.3.3 for biodiesel, and 4.4.3 for BioLPG.

Table 22 presents a synthesis of the available evidence in each section and the best estimates available for emission factors at the current time.

Note that air pollutant emissions have not been included in the modelling exercise which is focussed on economic and greenhouse gas impacts. It should also be noted that due to the rural nature of many off-gas grid properties, any emissions savings are unlikely to have a significant impact on local air quality, but the impact may be more significant at the national scale. The exception to this is properties still using coal for space and water heating.

Table 22. Best estimates for emission factors of air pollutants by fuel type

Product Type	PM		NOx		SO_2		CO		GHGs (CO_2e)	
	g/MWH		g/MWH		g/MWH		g/MWH		kg/MWH	
Oil-fired boiler	6.8	H	183.6	H	23.5	H	205.2	H	260	H
LPG boiler	0.14	H	170.8	H	1.0	H	87.1	H	230	H
Solid fuel (coal)	1146	M	448	M	2925	M	17,622	M	363	H
Bioliquid heating systems:	-		-		-		-		-	
Converted oil-fired boiler (B10K)	6.4	L	171.5	M	21.2	L	186.7	L	238	L
Converted oil-fired boiler (B30K)	5.6	L	156.3	M	16.5	L	100.0	L	193	L
Converted oil-fired boiler (B50K)	4.8	L	130.5	M	11.9	L	20.0	L	148	L
Dedicated biodiesel boiler (B100)	2.7	M	130.5	M	0.2	L	20.5	L	36	M
Vegetable oil-fired boiler	-I.E-		-I.E-		-I.E-		-I.E-		25	L
UCO-fired boiler	-I.E-		-I.E-		-I.E-		-I.E-		6	L
BioLPG boiler	0.14	H	170.8	H	1.0	H	87.1	H	123	L

Level of confidence is indicated by L (low), M (medium) or H (high). -I.E- Insufficient evidence to quantify within acceptable level of confidence.

Emission factors have been sourced from the NAEI where available and from the preceding sections where unavailable. Emission factors for blends have been scaled. For example, total GHG and SO_2 emissions reduce with increasing biodiesel content. They are therefore able to be scaled based on the ratio of biodiesel to kerosene. This is not necessarily true for PM, NOx and CO emissions which are far more dependent on combustion conditions and the optimisation of the operating parameters of the boiler.

As discussed in section 4.3.3, there is mixed evidence for the emissions of PM, NOx and CO for domestic scale biodiesel boilers and blends. Some studies have reported increases in CO and PM, but this is thought to be due to poor boiler performance. Where the boiler has been optimised for a given fuel type, CO emissions are up to 91% lower and PM emissions are up to 77% lower for biodiesel than heating oil (section 4.3.3). NOx is far more uncertain, but in the table above we assume the trends reported in Esarte et al. [61] which showed up to a 30% reduction for a B50K blend compared to kerosene.

7 Gap analysis

This section presents an analysis of knowledge gaps identified throughout the project.

7.1 Emissions

Standard emissions factors (EF's) are available through the HMT Green Book, BRE SAP 10.0 and through UK GHG Emission Factors for Company Reporting. The EF's used in this work are described in the individual sub-sections. Although as they were available for a limited number of fuels, it was necessary to apportion some values for blended fuels due to lack of published data. For example, GHG emission factors for a B50K are the sum of 50% that of biodiesel and 50% that of kerosene. This will not necessarily be true in actuality, but it provides an acceptable approximation. Recently a number of specifications have been released for B30K including OFTEC fuel specifications, Concawe fuel handling guidance, and SAP 10.0 emission factors. Where available, this information has been utilised to inform the analysis and to further validate the assumptions applied elsewhere.

It has also been necessary to make a number of assumptions about the fuel types and their origins which, as discussed previously, have an impact of the overall carbon savings. For example, virgin vegetable oil has been assumed to be rapeseed oil because it is the most widely available crop in the UK and is the most suitable for heating applications due to its low CFPP. Biodiesel at various blends is assumed to be used cooking oil methyl ester (UCOME), which is the dominant feedstock for biodiesel consumed in the UK. However, as discussed in section 4.3.3, the feedstock type and origin can increase or decrease the lifecycle GHG emissions by a factor of two or more. The feedstock country of origin is not taken into account in this work, since RTFO shows that it is sourced from 70 different countries around the world. The country of origin stated in table RTFO-05 is the origin of the raw UCO, not where it is converted into biodiesel; therefore, the country of manufacture is often unknown.

Further work would be required to analyse fuel supply chains in depth, to better understand the raw material source and processing steps involved, which inevitably impact on the overall carbon savings. Furthermore, additional work would be required to better understand the impacts of bioliquid heating systems on air quality. A large amount of work has been carried out assessing the impacts of bioliquids and blends on engines for transport applications, but only a small number of studies have focussed on small-scale boiler applications.

7.2 Costs and economics

The prices and costs used in the modelling represent the cost to the consumer. The fuel country of origin is not taken into consideration as most fuels are globally traded; whether it is domestic or imported has little bearing on cost when price volatility is so prevalent, and it is subject to many externalities.

Maintenance costs are largely unknown for domestic scale bioliquid systems. Further work would therefore be advised in this area, to verify or refine data which at present can only be extrapolated from the fossil-fuelled equivalent systems. Due to the nature and source of bioliquid fuels, faults and repairs may become more frequent or significant. Repair requirements may reduce from once every

3.5 years to once every 1.5 years, based on discussions with industry and our understanding of consumers behaviour when it comes to servicing requirements on existing fossil-based systems. Common reasons for emergency callouts for condensing boilers include blockages in condensate pipes due to ice formation in cold weather. For bioliquid systems, extreme cold weather incidents may lead to fuel crystallisation and blockages in fuel supply lines, filters and injectors. Other common failures for B100 systems may include injectors and fuel pump seals, which may require more regular replacement at increased cost.

A large, yet unknown number of off-gas grid properties have an installed iron range cooker, such as AGA's. In many rural households these appliances are a central feature of the home and can be fuelled by electricity, gas, oil or solid fuel. In cases where the appliances are fuelled by oil, the conversion to B30K or B100 may not be possible or may add considerable expense to the cost of fuel switching which, together which other social aspects, may influence consumer receptiveness.

A knowledge gap exists on the number of these appliances that are installed, how capable they are to operate using bioliquids, and how this might affect the consumer. Initial discussions with AGA Rangemaster found that current appliances are not compatible with bioliquids, and that many appliances require 'premium kerosene' which contains fuel additives (see section below on Technical Issues).

7.3 Supply chain issues

There is a knowledge gap surrounding the impact of obligations to blend on supply chains. As described in section 3.6 , there is very limited capacity in UK terminals and distribution hubs, and therefore significant investment would be required in the infrastructure needed to support multiple blend options.

In order for supply chains to adapt to additional fuel-options being introduced, a transition period would be required and it is not yet well understood how this transition may occur in practice, and how adaptable fuel producers, suppliers and distributors can be to accommodate the additional needs. The impact on supply and distribution infrastructure of making multiple fuel types available would need to be investigated further to determine the level of investment required and also the practical challenges that may arise. For example, it is recommended that storage tanks for B100 fuels be reduced in size in order to increase fuel turnover, but this would require more regular fuel deliveries and potentially more investment in distribution vehicles by fuel suppliers.

7.4 Fuel availability

The future availability of bioliquids is dependent on a wide array of different factors, including rising demand in other sectors and the cost-competitiveness of the domestic heating market. The UK was one of the top oil producers in Europe in 2016, with oil import dependency at just 34% [10]. In order to satisfy future bioliquid demand, the UK off-gas grid heating sector may be more reliant on foreign imports.

According to the IEA's New Polices Scenario (NPS)[36], oil demand in Europe is forecast to reduce from 13 million barrels per day (mb/d) in 2017 to 9 mb/d in 2040. However, this reduction is offset by demand increases in Asia and the Middle East, with total oil demand increasing by 12% over the same period. However, there are strong regional and sectoral differences. Total kerosene demand increases by 3 mb/day in the NPS and decreases by 1.4 mb/day in the sustainable development scenario (SDS), with increase driven principally by the aviation sector. LPG demand is forecast to increase in both scenarios; by 3.9 mb/d in the NPS and 1.9 mb/d in the SDS.

The electrification and decarbonisation of transport is forecast to significantly reduce demand for petroleum and diesel (petroleum demand reduces by 12.5 mb/d in the SDS). Total biofuel demand is forecast to increase by over 130% between 2017 and 2040 under the NPS. It is not clear at the present time whether UK Government policy to support the electrification of transport will increase the availability of bioliquids for heat, or whether demand in other sectors will limit this availability.

Further work would be required to assess the impact of competing markets on fuel costs, and the consequences this would have on fuel availability for the domestic heating sector.

7.5 Technical issues

As previously stated, a number of fuel specifications have been published for fossil heating fuels, B100 FAME and more recently for B30K. However clearer guidance is required specifically for the domestic heating sector on the best practice for bioliquid conversion, blending and installation of new equipment. Such a guidance document could consolidate information given in published standards such as BS 2869, BS EN 14214, BS EN 590, Building Regulations Document J, as well as industry guidance such as OPS 24 and the OFTEC Going Green Guide.

There is a knowledge gap on the potential of fuel additives to overcome some of the stability and cold weather problems of bioliquids. A large number of UK fuel suppliers already offer fuel additives for kerosene heating oil which are reputed to have the following benefits:

- Fuel stabilisation
- Inhibit sludge formation
- Reduce deposit build up
- Increase fuel longevity
- Reduce service costs
- Increase system efficiency
- Potential emissions reduction

Consumers have the option to purchase fuel that already contains additives, marketed as 'premium kerosene' which typically costs 4-6 p/litre more than standard kerosene. Consumers may also purchase additives directly, which typically costs £15-20 to treat 1000 litres of fuel (1.5-2.0 p/litre).

[36] Scenario descriptions and assumptions are given in the IEA World Energy Outlook 2018, available at https://www.iea.org/weo2018/fuels/

In addition to fuel additives, there is potential to improve the storage and handling properties of bioliquids through blending with conventional fossil fuels. However, it is unclear what effect the blending concentration has on properties such as CFPP and the impact this has on availability and price. For example, B100 made from tallow has a high CFPP but a B30K using tallow may have a suitable CFPP, though this is unknown. Further work would be required in this area, to verify claims, to quantify the benefits and to understand how costs may be impacted by the inclusion of additives.

A knowledge gap exists surrounding the fuel blend compatibility of boilers which are designed for B10K, B30K, B50K and B100. Feedback from manufacturers during the stakeholder interviews has suggested that up to 30% biodiesel could be used in existing oil boilers with minimal adaptions, other than a service visit by a qualified engineer. Blends up to 50% may cause deposits to build up at the combustion-head and lead to lower efficiencies and potentially higher incidence of breakdowns. Pre-heating may be required prior to the nozzle head to overcome some of these issues, but 30-50% blends may lead to corrosion or sedimentation in the storage tank. Therefore above 30% it is recommended that a new B100 boiler be installed and all components of the fuel handling system be manufactured from compatible materials including stainless steel tubing and Viton® seals, for example.

Once installed, a B100 or dedicated biodiesel boiler should be capable of burning lower blends (i.e. a high proportion of kerosene) but a service engineer would be required to attend the property and optimise the boiler for a given blend ratio. It is unclear at the present time what effect the use of lower blends in a system designed for high blends might have on maintenance costs, emissions or boiler lifetime.

8 Conclusions

There is a clear and urgent need to further decarbonise the UK economy and the heat sector is a subject of focus for a number of reasons. Specifically, properties that are off the gas grid present a significant opportunity for decarbonisation, with total greenhouse gas emissions of over 7.2 million tonnes of CO_2e per year and a market value of over £1.1 billion per year for fuel supply alone (see sections 1.1.2 and 1.1.3). The key off-gas fuel type is kerosene (1.1 million homes in Great Britain), with fewer users of LPG (0.19 million homes) and solid fuels (0.2 million homes).

Bioliquids have a number of advantages over solid fuels including higher energy density, greater ease of distribution and lower emissions of air pollutants. Additional capital expenditure may not be possible for some properties which already have a higher level of fuel poverty than those which are on the gas-grid. The key disadvantages of bioliquids for heating include fuel availability, given competing markets and lack of suppliers offering this fuel type, and technology availability for boilers, tanks and component parts compatible with higher blends or fully bioliquid fuels.

The key bioliquids of interest in this work are FAME biodiesel, virgin vegetable oils, used cooking oils, bio-oil from fast-pyrolysis and BioLPG (biopropane). In addition, the potential of biodiesel to be blended with kerosene is examined at 10%, 30% and 50% blends (e.g. B30K).

8.1 Key findings

New boilers and those installed within the last five years, which equates to around one third of the current boiler-stock, should be compatible with 10-30% biodiesel blends. Blends higher than 30% require a step change in boiler design and fuel handling, due to issues with materials compatibility and injectors. Use of B30K could therefore be adopted relatively quickly, whereas higher blends would require a longer adaptation period. The main barrier is the cost of modification of existing boiler systems which makes the deployment of bioliquid heating an expensive option. Therefore, uptake of higher blends is unlikely to grow without policy intervention.

The number of blend options has been raised as a concern by fuel suppliers and distributors; significant investment may be required to accommodate and distribute a wider range of fuel options, and in many cases space or capacity simply may not exist for some suppliers to extend the fuel range.

There are knowledge gaps surrounding the fuel properties of blends and the suitability of biodiesel sourced from different feedstocks for heating purposes. B100 fuels may exhibit cold weather issues, depending on their composition and feedstock, though B100 based on rapeseed oil or used cooking oil is expected to meet to current standard requirements for winter fuel grades. However, biodiesel availability may be limited by competing markets in the UK and overseas, and greater volumes of UCO are now being imported to the UK than ever before.

The use of raw vegetable oils or refined cooking oils for heating has very limited applicability in the domestic sector due to fuel inhomogeneity, high viscosity and cold weather problems. Similarly, fast-pyrolysis bio-oil (FPBO) is not suitable for domestic applications due to its high acidity, moisture content and poor storage properties. The volume of FPBO produced is increasing and standards now exist for the use of FPBO in industrial boilers, but heated or agitated tanks are not practical at the domestic scale.

BioLPG (biopropane) has great potential because it is a drop-in fuel and requires no modifications to the boiler or fuel handling system. It is already commercially available in the UK and is produced as a by-product of a number of processes, including gasification and hydrotreating of vegetable oils. LPG also has the lowest emission factors of air pollutants compared to heating oil, biodiesel and blends; and, fossil-LPG and BioLPG have 19% lower and 93% lower lifecycle GHG emissions than heating oil respectively.

The scale of opportunity is clearly significant, however the significance of the challenge and the additional costs involved cannot be underestimated. Uptake is likely to be constrained by both technology and fuel availability, and ongoing fuel and maintenance costs for consumers are likely to be increased, in some instances significantly. Given time, supply chains will be able to adapt and product and fuel availability will increase, whilst at the same time costs should reduce. However, there remain uncertainties around the timeframe within which these changes could be achieved.

Further work is required in several areas, to verify costs and emissions values, and to investigate the supply chain constraints relating to the production, storage and distribution of suitable fuels should bioliquids be introduced as a domestic heating fuel in the UK.

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Appendices

Appendix A – Global Supply of Biodiesel to the UK in 2017/18

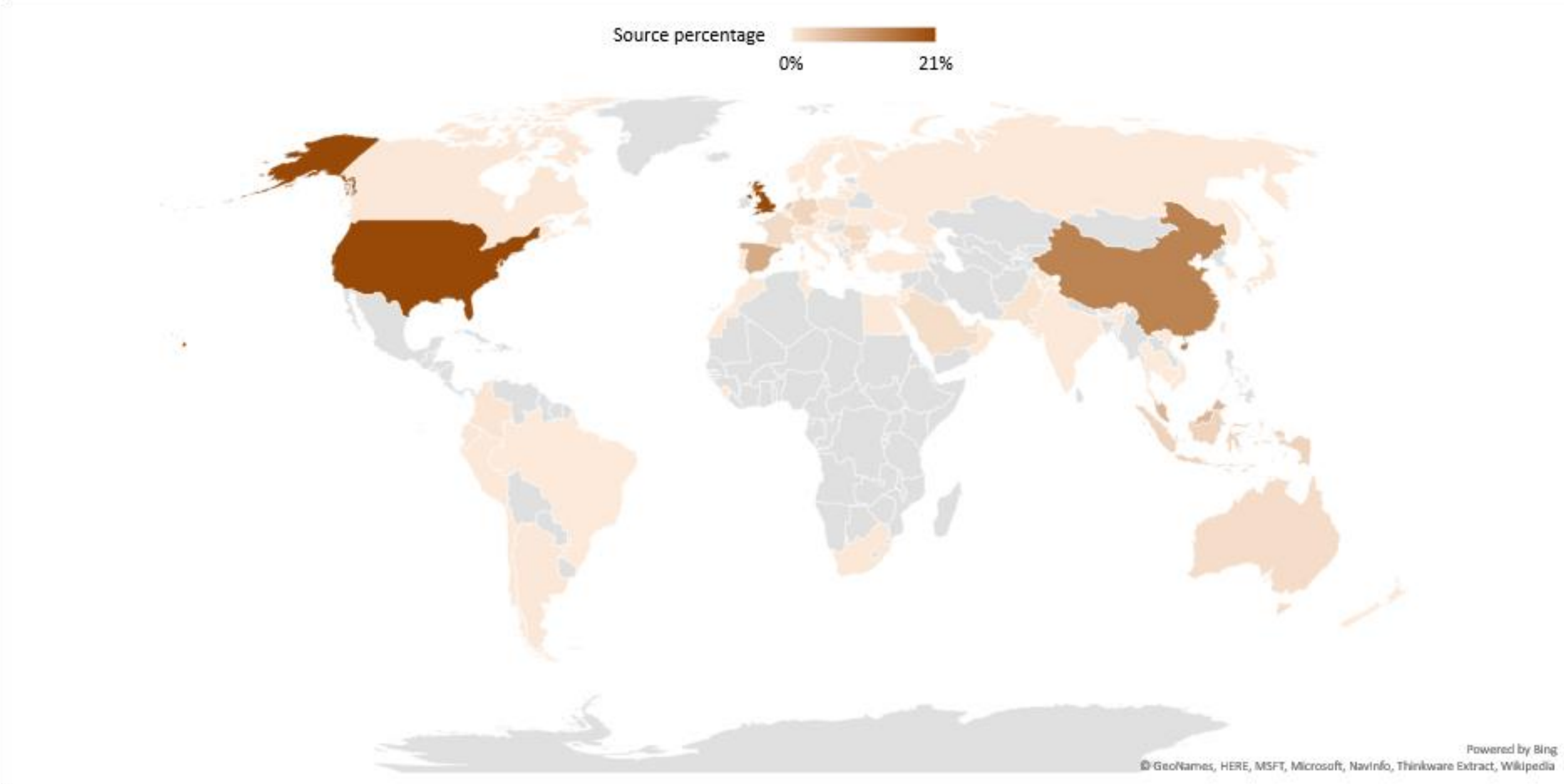

Image shows percentage contributions by country of feedstocks to UK biodiesel consumption under the RTFO. Grey = no data. Data Source: RTFO Biofuel statistics: Year 10 (April 2017 to April 2018), report 5.

Appendix B – Comparison of Fuel Properties

Property	Unit	Kerosene	Gas oil	UCO	Virgin vegetable oil (rapeseed)	B100 biodiesel	B30K	Pyrolysis oil	LPG
Ref		[135]	[135]	[86][87][77]	[138], [139][54]	[140]	[76]	[38][141]	[142]
FAME content	% v/v	-	<7	-	-	>96.5	29.97	-	-
Water content	mg/kg	Free from undissolved water	<200			<500	99	≤ 30	
Nitrogen [61]	mg/kg	393	45	18	64	20-70	12.2	679-7830 dependent on feedstock	Trace
Sulphur	mg/kg	<400 (Class C1) <1000 (Class C2)	<1000	2	100	<10	160	1000 (Grade 1) 500 (Grade 2)	<200
Ash content	% m/m	0.002	0.01	Dependent on degree of filtering	0.05	0.02	<0.001	0.25 (Grade 1) 0.05 (Grade 2)	
NET CV	MJ/kg	42.8	42.569	35.82	37.6	>35	41.047	≥ 14.0	45.916
Density at 15°C	kg/m3	775-840	820	898	910	860-900	826	≤ 1300	517
Kinematic viscosity at 40°C	mm2/s	1.00 - 2.00	2.00 - 5.00	45.34	37.3	3.5-5.0	1.713	125 (Grade 1) 50 (Grade 2)	[gas]
Flash point	°C	>43 (Class C1) >38 (Class C2)	>55	305	246	>101	48	≤ 35	-104
Cloud point	°C	-11		24	-3.9	-3 to +16	-8		
Pour point	°C	-13		9	-32		-18	≤ -9	
CFPP	°C	-40?	-4°C (summer) - 12°C (winter)	9	-8.04943	-20 - +5	-14	50	
Cetane number			45	30	37.5	66 (>51)			-2

Appendix C – Off-Gas Grid Property Case Studies

Property 1 - Detached

This case study was undertaken on 11/01/19. It provides a technical assessment of the issues associated with replacement of an existing domestic oil boiler system into a system capable of operating using bioliquids. It includes consideration of the practical, technical and cost issues.

PROPERTY DESCRIPTION:

- Detached Farmhouse, stone-built property, built circa. 1800's.
- 4 bedrooms, 2 bathrooms, one kitchen, 2 reception rooms.
- Wet heating central heating system throughout.
- Domestic Hot Water (DHW) via cylinder located in upstairs bathroom.

EXISTING OIL FUEL TANK:

- Bunded cylindrical plastic tank, installed circa. 8 years ago (relocated to field 2017).
- 2,500 litres
- Externally located in adjacent field, on flags as a plinth,
- Fuel feed pipe; copper 10mm microbore pipe feeding through field boundary, into courtyard and into utility room.
- Distance of fuel feed pipe 18m externally (mainly buried) and 1.5m internally

SEQUENCE OF WORKS TO REPLACE FUEL TANK:

	Works	Hours	Personnel
1.	Isolation of oil from tank to boiler	0.5	OFTEC qualified engineer
2.	Isolation of tank	0.5	OFTEC qualified engineer
3.	Flush oil feed line	0.5	OFTEC qualified engineer
4.	Removal of filter, fuel feed pipe	6.0	OFTEC qualified engineer
5.	Drain oil tank	1.0	Waste licence carrier
6.	Dispose of waste oil	0.5	Waste licence carrier
7.	Remove oil tank	1.0	Waste licence carrier

Notes:

- Oil feed line is most difficult part of tank removal – buried through field and disappears under stone flags and steps before going into utility room.
- Tank is located on its own in this instance would be relatively simple; specialist equipment required would involve lifting and carrying equipment (fork-lift, front-end loader, etc.).
- Typical cost for isolation and safe removal / disposal of steel oil tank circa. £640 - reference National Trust, Ravenscar district heating (May 2018, Northern Tank Services).
- Waste Transfer / Disposal notice must be obtained for above oil tank works.

Likely costs:

- Labour time is estimated at 10 hours and the rate is assumed to be £45/hour. Therefore, labour costs are estimated at £450.00. The old oil tank would cost ~£640 to remove off site. So total costs are estimated at £1,090.00. This excludes the cost of supplying and fitting a new bioliquids tank.

EXISTING BOILER DESCRIPTION:

- Warmflow 22kW-36kW system boiler, providing hot water and heating
- Located in utility room, to the rear of kitchen
- Domestic Hot Water via. cylinder located in bathroom
- Installed 2016 (new)
- Riello RDB Burner

SEQUENCE OF WORKS TO REMOVE BOILER:

	Works	Hours	Personnel
1.	Isolation of oil tank from boiler	0.5	OFTEC qualified engineer
2.	Isolation of boiler from heating system	2.0	Heating engineer
3.	Electrical isolation	1.0	Electrician
4.	Removal of boiler from property	0.5	Heating engineer

Notes:

- Relatively simple operation to remove boiler; isolation and reconnection into existing heating and hot water system. Existing 2-port controls and programmer would be compatible with a new boiler.

Likely costs:

Labour time is estimated at 4 hours and the rate is assumed to be £45/hour. Therefore, labour costs are estimated at £180. The old oil boiler would cost ~£100 to remove off site. So total costs are estimated at £280. This excludes the cost of supplying and fitting a new bioliquids oil boiler.

OVERALL COSTS:

- Removal of oil tank: £1,090.00 (excludes the cost of supplying and fitting a new bioliquid tank)
- Removal of oil boiler: £280.00 (excludes the cost of supplying and fitting a new bioliquid boiler)

Total costs: £1,370.00

Property 2 – Semi-detached

This case study was undertaken on 10/01/19. It provides a technical assessment of the issues associated with replacement of an existing domestic oil boiler system into a system capable of operating using bioliquids. It includes consideration of the practical, technical and cost issues.

PROPERTY DESCRIPTION:

- Farmhouse, stone-built property, built circa. 1800's
- 4 bedrooms, 1 bathroom, one kitchen, 3 reception rooms
- Semi-detached (small farm cottage adjacent to farmhouse)
- Wet heating central heating system throughout
- Domestic Hot Water (DHW) via cylinder located in upstairs bathroom

EXISTING OIL FUEL TANK:

- Steel, single skinned tank, installed circa. 18 years ago
- 2,000 litres
- Externally located, mounted on concrete blockwork
- Fuel feed pipe; copper 10mm microbore pipe feeding through wall and into utility room
- Fuel feed pipe branches to feed AGA in kitchen
- Distance of fuel feed pipe 4m externally (mainly buried) and 2m internally

SEQUENCE OF WORKS TO REPLACE FUEL TANK:

In this instance there are no basic constraints to a full replacement of the oil tank. The scope of work is noted below:

	Works	Hours	Personnel
1.	Isolation of oil from tank to boiler	0.5	OFTEC qualified engineer
2.	Isolation of tank	0.5	OFTEC qualified engineer
3.	Flush oil feed line	0.5	OFTEC qualified engineer
4.	Removal of filter, fuel feed pipe	1.5	OFTEC qualified engineer
5.	Drain oil tank	1.0	Waste licence carrier
6.	Dispose of waste oil	0.5	Waste licence carrier
7.	Remove oil tank	2.0	Waste licence carrier

Notes:

- Typical cost for isolation and safe removal / disposal of steel oil tank circa. £640 - reference National Trust, Ravenscar district heating (May 2018, Northern Tank Services).
- Waste Transfer / Disposal notice must be obtained for above oil tank works.
- Removal of oil tank in this instance would be relatively simple; specialist equipment required would involve lifting and carrying equipment (fork-lift, front-end loader, etc.).

Likely costs:

Labour time is estimated at 6.5 hours and the rate is assumed to be £45/hour. Therefore, labour costs are estimated at £292.50. The old oil tank would cost ~£640 to remove off site. So total costs are estimated at £940.50. This excludes the cost of supplying and fitting a new bioliquids tank.

EXISTING BOILER DESCRIPTION:

- Firebird 26kW system boiler, providing hot water and heating
- Located in utility room (in a single storey extension to main property)
- Domestic Hot Water via cylinder located in bathroom
- Installed in 2012
- Riello RDB Burner

SEQUENCE OF WORKS TO REMOVE BOILER:

	Works	Hours	Personnel
1.	Isolation of oil tank from boiler	0.5	OFTEC qualified engineer
2.	Isolation of boiler from heating system	2.0	Heating engineer
3.	Electrical isolation	1.0	Electrician
4.	Removal of boiler from property	0.5	Heating engineer
5.	Joinery works to repair work surface	2.0	Joiner

Notes:

- AGA provides cooker (and space heating) for kitchen. Any removal / replacement of oil tank must take this into consideration. Replacement heating and cooker required for kitchen, or oil tank to be retained for AGA alone.
- Relatively simple operation to remove boiler; isolation and reconnection into existing heating and hot water system. Existing 2-port controls and programmer would be compatible with a new boiler.

Likely costs:

Labour time is estimated at 6 hours and the rate is assumed to be £45/hour. Therefore, labour costs are estimated at £270. The old oil boiler would cost ~£100 to remove off site. So total costs are estimated at £370. This excludes the cost of supplying and fitting a new bioliquids oil boiler.

OVERALL COSTS:

- Removal of oil tank: £940.50 (excludes the cost of supplying and fitting a new bioliquid tank)
- Removal of oil boiler: £370.00 (excludes the cost of supplying and fitting a new bioliquid boiler)

Total costs: £1,210.50

Property 3 – Semi-detached

This case study was undertaken on 11/01/19. It provides a technical assessment of the issues associated with replacement of an existing domestic oil boiler system into a system capable of operating using bioliquids. It includes consideration of the practical, technical and cost issues.

PROPERTY DESCRIPTION:

- Semi-Detached House, stone-built property, built circa. 1880's.
- 5 bedrooms, 2 bathrooms, kitchen, 3 reception rooms. Attached annex.
- Wet heating central heating system throughout, split into two zones.
- Domestic Hot Water (DHW) via cylinder located in main house.
- AGA in kitchen – also fed from the oil tank.

EXISTING OIL FUEL TANK:

- Bunded cylindrical plastic tank, installed circa. 10 years ago located in courtyard to the rear of the property.
- 2,500 litres
- Fuel feed pipe; copper 10mm microbore pipe feeding around the courtyard and into the utility room to rear of main property.
- Majority of oil feed pipe is covered with concrete field boundary, into courtyard and into utility room
- Distance of fuel feed pipe 18m externally (mainly buried) and 15m externally, and 8m internally to reach the boiler.

SEQUENCE OF WORKS TO REPLACE FUEL TANK:

	Works	Hours	Personnel
1.	Isolation of oil from tank to boiler	0.5	OFTEC qualified engineer
2.	Isolation of tank	0.5	OFTEC qualified engineer
3.	Flush oil feed line	0.5	OFTEC qualified engineer
4.	Removal of filter, fuel feed pipe	6.0	OFTEC qualified engineer
5.	Drain oil tank	1.0	Waste licence carrier
6.	Dispose of waste oil	0.5	Waste licence carrier
7.	Remove oil tank	1.0	Waste licence carrier

Notes:

- Tank is located in a courtyard to the rear of the property which is difficult to access. Possibly requiring a small crane / front-end loader to lift tank out of courtyard circa. 4.5m below height of nearest road access.
- Typical cost for isolation and safe removal / disposal of steel oil tank circa. £640 - reference National Trust, Ravenscar district heating (May 2018, Northern Tank Services).
- Consideration to be given to implications of AGA removal – no heating in kitchen, cooking etc.
- Waste Transfer / Disposal notice must be obtained for above oil tank works.

Likely costs:

- Labour time is estimated at 10 hours and the rate is assumed to be £45/hour. Therefore, labour costs are estimated at £450.00. The old oil tank would cost ~£640 to remove off site. So total costs are estimated at £1,090.00. This excludes the cost of supplying and fitting a new bioliquids tank.

EXISTING BOILER DESCRIPTION:

- Warmflow 22kW-36kW system boiler, providing hot water and heating
- Located in utility room, to the rear of kitchen
- Domestic Hot Water via cylinder located in bathroom
- Installed 2016 (new)
- Riello RDB Burner

SEQUENCE OF WORKS TO REMOVE BOILER:

	Works	Hours	Personnel
5.	Isolation of oil tank from boiler	0.5	OFTEC qualified engineer
6.	Isolation of boiler from heating system	2.0	Heating engineer
7.	Electrical isolation	1.0	Electrician
8.	Removal of boiler from property	0.5	Heating engineer

Notes:

- Boiler located in basement of property;

Likely costs:

Labour time is estimated at 4 hours and the rate is assumed to be £45/hour. Therefore, labour costs are estimated at £180. The old oil boiler would cost ~£100 to remove off site. So total costs are estimated at £280. This excludes the cost of supplying and fitting a new bioliquids oil boiler.

OVERALL COSTS:

- Removal of oil tank: £1,090.00 (excludes the cost of supplying and fitting a new bioliquid tank)
- Removal of oil boiler: £280.00 (excludes the cost of supplying and fitting a new bioliquid boiler)

Total costs: £1,370.00

Property 4 - Terraced

This case study was undertaken on 10/01/19. It provides a technical assessment of the issues associated with replacement of an existing domestic oil boiler system into a system capable of operating using bioliquids. It includes consideration of the practical, technical and cost issues.

PROPERTY DESCRIPTION:

- End terrace, stone-built agricultural workers property, built circa. 1800's.
- 2 bedrooms, 1 bathroom, one kitchen, one living room.
- Wet heating central heating system throughout.
- Domestic Hot Water (DHW) via cylinder located in upstairs bathroom.

EXISTING OIL FUEL TANK:

- Steel, single skinned tank, installed circa. 18 years ago.
- 2,000 litres
- Externally located, mounted on concrete blockwork.
- Fuel feed pipe; copper 10mm microbore pipe feeding through wall and into utility room.
- Distance of fuel feed pipe 4m externally (mainly buried) and 2m internally

SEQUENCE OF WORKS TO REPLACE FUEL TANK:

In this instance there are no basic constraints to a full replacement of the oil tank. The scope of work is noted below:

Works	Hours	Personnel
1. Isolation of oil from tank to boiler	0.5	OFTEC qualified engineer
2. Isolation of tank	0.5	OFTEC qualified engineer
3. Flush oil feed line	0.5	OFTEC qualified engineer
4. Removal of filter, fuel feed pipe	1.5	OFTEC qualified engineer
5. Drain oil tank	1.0	Waste licence carrier
6. Dispose of waste oil	0.5	Waste licence carrier
7. Remove oil tank	2.0	Waste licence carrier

Notes:

- Typical cost for isolation and safe removal / disposal of steel oil tank circa. £640 - reference National Trust, Ravenscar district heating (May 2018, Northern Tank Services).
- Waste Transfer / Disposal notice must be obtained for above oil tank works.
- Removal of oil tank in this instance would be relatively simple; specialist equipment required would involve lifting and carrying equipment (fork-lift, front-end loader, etc.).

Likely costs:

Labour time is estimated at 6.5 hours and the rate is assumed to be £45/hour. Therefore, labour costs are estimated at £292.50. The old oil tank would cost ~£640 to remove off site. So total costs are estimated at £940.50. This excludes the cost of supplying and fitting a new bioliquids tank.

EXISTING BOILER DESCRIPTION:

- Warmflow 15kW system boiler
- Located in utility room (in a single storey extension to main property)
- Domestic Hot Water via cylinder located in bathroom
- Installed 2012
- Riello RDB Burner

SEQUENCE OF WORKS TO REMOVE BOILER:

	Works	Hours	Personnel
1.	Isolation of oil tank from boiler	0.5	OFTEC qualified engineer
2.	Isolation of boiler from heating system	2.0	Heating engineer
3.	Electrical isolation	1.0	Electrician
4.	Removal of boiler from property	0.5	Heating engineer
5.	Joinery works to repair work surface	2.0	Joiner

Notes:

- Relatively simple operation to remove boiler; isolation and reconnection into existing heating and hot water system. Existing 2-port controls and programmer would be compatible with a new boiler.

Likely costs:

Labour time is estimated at 6 hours and the rate is assumed to be £45/hour. Therefore, labour costs are estimated at £270. The old oil boiler would cost ~£100 to remove off site. So total costs are estimated at £370. This excludes the cost of supplying and fitting a new bioliquids oil boiler.

OVERALL COSTS:

- Removal of oil tank: £940.50 (excludes the cost of supplying and fitting a new bioliquid tank)
- Removal of oil boiler: £370.00 (excludes the cost of supplying and fitting a new bioliquid boiler)

Total costs: £1,210.50

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The Bioeconomy Consultants NNFCC

NNFCC, Biocentre,
York Science Park,
Innovation Way,
Heslington, York,
YO10 5DG.

Phone: +44 (0)1904 435182
Fax: +44 (0)1904 435345
E: enquiries@nnfcc.co.uk
Web: www.nnfcc.co.uk