



Biopropane: Feedstocks, Feasibility and our Future Pathway

Prepared for Liquid Gas UK

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Executive Summary

Liquefied Petroleum Gas (LPG) is an extremely versatile low-emission fossil fuel which has a variety of applications in the heating, transport and industrial sectors. LPG consists of mostly propane and/or butane, which are typically produced as a by-product of crude oil refining and natural gas processing. Biopropane (or bioLPG) is chemically identical to fossil propane and so can be used as a drop-in fuel in the same applications, but with added potential for greenhouse gas mitigation. LPG has the environmental benefits of a gas but is also relatively easily liquefied under mild pressurisation, which allows it to be easily transported, distributed and stored. As a liquid, LPG has a higher energy density than many other low-emission fuels such as compressed/liquefied natural gas or biomethane and is currently more commercially available.

In heating applications, LPG is used for space and water heating in the UK domestic, commercial and agricultural sectors (including crop drying, animal rearing and greenhouse heating). Thousands of off-gas grid homes and businesses rely on LPG as a bulk-delivered energy source for use in boilers and cooking hobs. In transport, LPG is used in spark ignition engines which is a lower-cost and lower-emission fuel than petrol and diesel. LPG is also used in non-road mobile machinery (e.g. forklift trucks), as well as portable equipment (e.g. water pumps) and fuel cells. Biopropane also has a number of potential applications in the industrial non-energy use sector, which accounts for over 50% of LPG consumed in the UK. Using biopropane instead of fossil LPG could reduce the lifecycle greenhouse gas emissions of petrochemical products and increase the bio-based content.

The Government has plans to phase out the use of high-carbon heating fuels during the 2020's and low-carbon biopropane has the potential to be used directly in the 193,000 homes that currently use LPG. In addition, there is potential to significantly reduce greenhouse gas emissions from off-gas grid homes and businesses by converting the 1.1 million homes that use heating oil to biopropane. Due to its versatility, biopropane can be used directly as a fuel in LPG boilers or it can be used in hybrid systems giving added flexibility to heat decarbonisation options.

Most biopropane is produced as a co-product of the hydrogenated vegetable oil (HVO) process, where vegetable oils are treated with hydrogen to produce renewable diesel or aviation fuel. HVO production is increasing in Europe, driven by renewable transport fuel targets, but there are currently no planned facilities in the UK, so the market is likely to be dependent on imports in the short- to medium-term without investment in domestic production. There is significant potential, however, for investment in indigenous production facilities in the UK. Opportunities include new HVO plants, co-processing at existing refineries and commercialising new and novel processes for biopropane synthesis.

A potential deployment pathway for a full switch from fossil- to biopropane in the UK by 2040 is considered feasible. HVO and co-processing are likely to be the dominant sources of biopropane during the 2020's, after which gasification and Fischer-Tropsch synthesis is likely to be the dominant production technology, utilising a range of feedstocks including lignocellulosic biomass and waste. In addition, there is likely to be a growing proportion of hydrogen used in HVO processes that is derived from renewable sources such as electrolysis, which will further reduce lifecycle greenhouse gas emissions of biopropane produced via this route adding to its attractiveness and credibility.

Glossary of key terms

Term	Description
APR	Aqueous phase reforming
Autogas	LPG for use as a transport fuel
BEIS	The Department for Business, Energy and Industrial Strategy
Bio-based oil	In the context of this report, this refers to any oil of biological origin used in a process to produce biopropane. It includes vegetable oils, FPBO, bio-crude and others.
Bio-crude	A viscous brown liquid formed from the hydrothermal liquefaction of biomass; similar to, but distinct from, FPBO.
Bio-DME	Bio-based dimethyl ether; can be blended up to 20% with LPG.
BioLPG	Bio-based LPG which is propane derived from renewable biological sources.
Biopropane	Analogous to BioLPG
Biosynthesis	Process to produce biopropane from microbes, e.g. fermentation.
CCC	Committee on Climate Change
CNG	Compressed natural gas
CV	Calorific value (energy density)
DfT	Department for Transport
DUKES	Digest of United Kingdom Energy Statistics
FAME	Fatty acid methyl ester; a type of biodiesel.
FPBO	Fast pyrolysis bio-oil; a viscous brown liquid formed from the pyrolysis of biomass.
FT-	Fischer-Tropsch synthesis
GHG	Greenhouse gas
HEFA	Hydroprocessed esters and fatty acids, analogous to HVO.
HTL	Hydrothermal liquefaction; a process for liquefying biomass.
HVO	Hydrotreated vegetable oil
kWh	Kilowatt hour, unit of energy.
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas derived from fossil fuels, mostly propane or butane although it could include lesser amounts of many different hydrocarbons.
MSW	Municipal solid waste
MTG	Methanol-to-gasoline synthesis
NOx	Nitrogen oxides
PM	Particulate matter
RDF	Refuse-derived fuel
RED	Renewable Energy Directive (2009/28/EC RED I, 2018/2001/EU RED II)
RHI	Renewable Heat Incentive
RTFC	Renewable Transport Fuel Certificate
RTFO	Renewable Transport Fuel Obligation
SO₂	Sulphur dioxide
UCO	Used cooking oil
ULEVs	Ultra-low emission vehicles

1 Introduction

Liquid Gas UK is the trade association for the Liquefied Petroleum Gas (LPG) industry in the UK, representing companies who are LPG producers, distributors, equipment and service providers, and vehicle convertors. Member companies cover over 99% of the total LPG distributed in the UK. The association takes a leading role in liaising and consulting with Government, legislators and policy makers with regards to sustainable energy policy. Liquid Gas UK is dedicated to the safe and progressive development of LPG with a focus on its role in providing low carbon heating and energy for homes and businesses that are located off the gas grid.

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.

On behalf of its membership, Liquid Gas UK commissioned this report to review the potential for biopropane produced or sourced for use in the UK, and to determine whether there is a credible pathway for biopropane supply that satisfies deep decarbonisation objectives for heating by the 2040s.

Biopropane 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, biopropane 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 biopropane to be the lowest cost and most practical bioliquid for off-grid heating. Furthermore, LPG has the lowest lifecycle CO₂e emissions of all fossil-based heating options, with emissions up to 20% lower for LPG than heating oil, and it also compares favourably with other low carbon options. Although emissions from biopropane are variable, dependent on initial feedstock, process type and efficiency, it is typically superior when compared to other low carbon options in terms of lifecycle CO₂e emissions.

Heating accounts for 47% of total final energy consumption in the UK (ECUK, 2019); 55% of which is accounted for by the domestic sector, mostly for space heating, but also for hot water and cooking. Evidently, 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 and the UK has been working to decarbonise the heat sector since the introduction of the Renewable Heat Incentive (RHI) Scheme in 2011. 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) (BEIS, 2017) and subsequent Future Framework for Heat in Buildings Call for Evidence (BEIS, 2018) 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 homes and businesses. Subsequently, in June 2019 the Government legislated for the UK's greenhouse gas reduction targets to be strengthened from an 80% reduction by 2050 to net zero by 2050.

Additionally, in January 2019 the UK's Clean Air Strategy (Defra, 2019) set out plans for dealing with all sources of air pollution, making our air healthier to breathe, protecting nature and boosting the economy. 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 coal and oil-fired heating will ensure this transition improves air quality while at the same time reducing carbon. For domestic/commercial heating, LPG and biopropane boilers have significantly lower emissions of PM, NO_x and SO₂ than solid fuels or heating oil. The same is true in transport, where switching from petrol or diesel to LPG/biopropane vehicles can help to improve air quality.

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. 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) (DUKES, 2018).

This report reviews the markets in more depth, identifying relevant policies and drivers, then quantifying current and future potential demand, before considering the supply chain, in terms of current and future potential production capacity, feedstock requirements and key constraints. The overall deployment potential, in terms of both supply and demand is then set against a timeline, to illustrate the potential contribution and impact biopropane could deliver towards the UK's 2040 decarbonisation targets. A series of high-level actions are then identified, which would need to be addressed in order to overcome production, supply or market constraints.

2 Market Opportunities

This section describes the current market for LPG, by sector, with a focus on relevant policies or other supporting measures, the scale of the opportunity for biopropane, and the resultant likely impact of introducing biopropane to each sector.

2.1 Current LPG market overview

Total demand for propane was 2.266 million tonnes in 2017 which was 2% shy of total supply. For butane, supply exceeded demand which was 0.745 million tonnes. As shown in Figure 1, demand has increased slightly since the year 2000, with the largest growth in the non-energy use and residential, commercial and agricultural sectors.

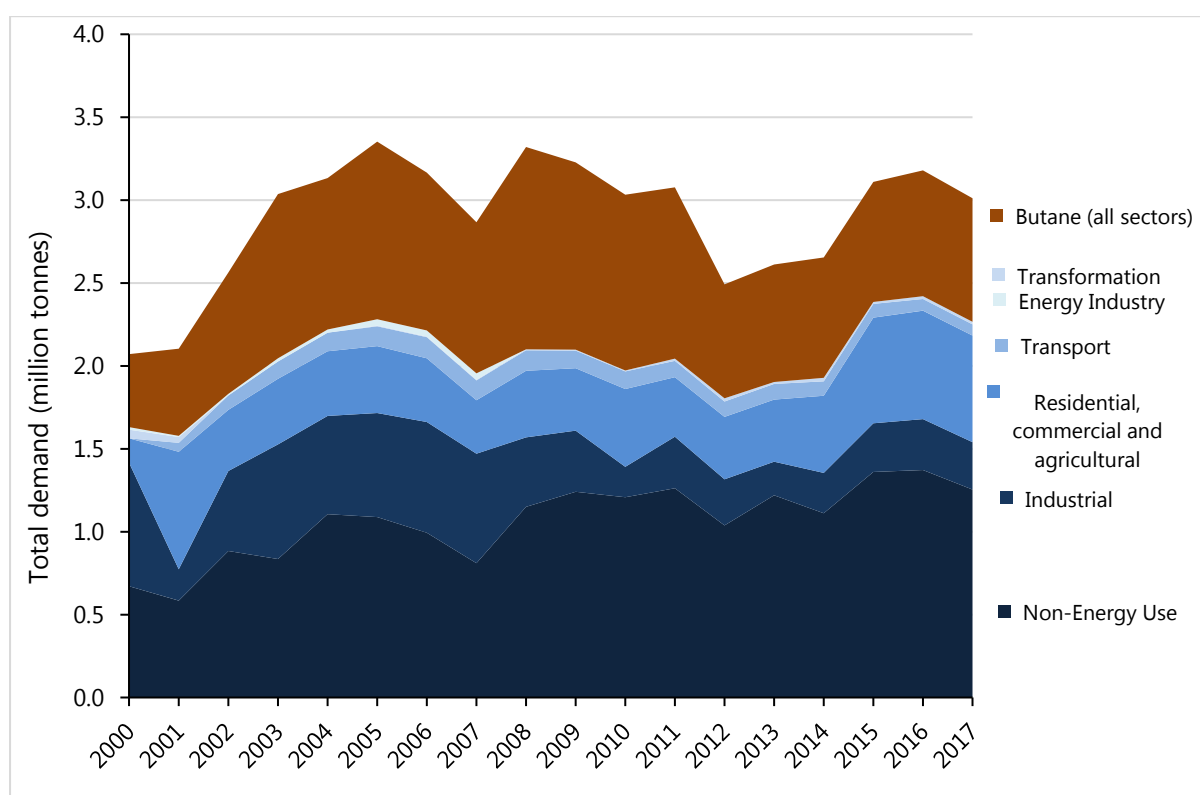


Figure 1. Propane and butane demand by sector, 2000-2017. Source: DUKES

Total UK propane demand has increased by 39% since the year 2000, whilst total butane demand has increased by 69%. Non-energy use of propane has doubled in the last ten years but use in industry for energy has declined. Consumption in the domestic and agricultural sectors has remained largely stable at 200-300 kt and 90-120 kt respectively. However, propane use in the commercial sector has increased dramatically since 2013, now at 344 kt.

As shown in Figure 2, 55% of propane and 54% of butane is consumed for non-energy use, which is principally use in the petrochemical industry. This comprises the manufacture of basic chemicals, fertilisers and nitrogen compounds, plastics and synthetic rubber in primary forms, basic pharmaceutical products and pharmaceutical preparations. Alongside propane and butane, typical

products delivered to and received from the petrochemical industry include: refinery gas, ethane, naptha, gas oil, petroleum coke and lubricants.

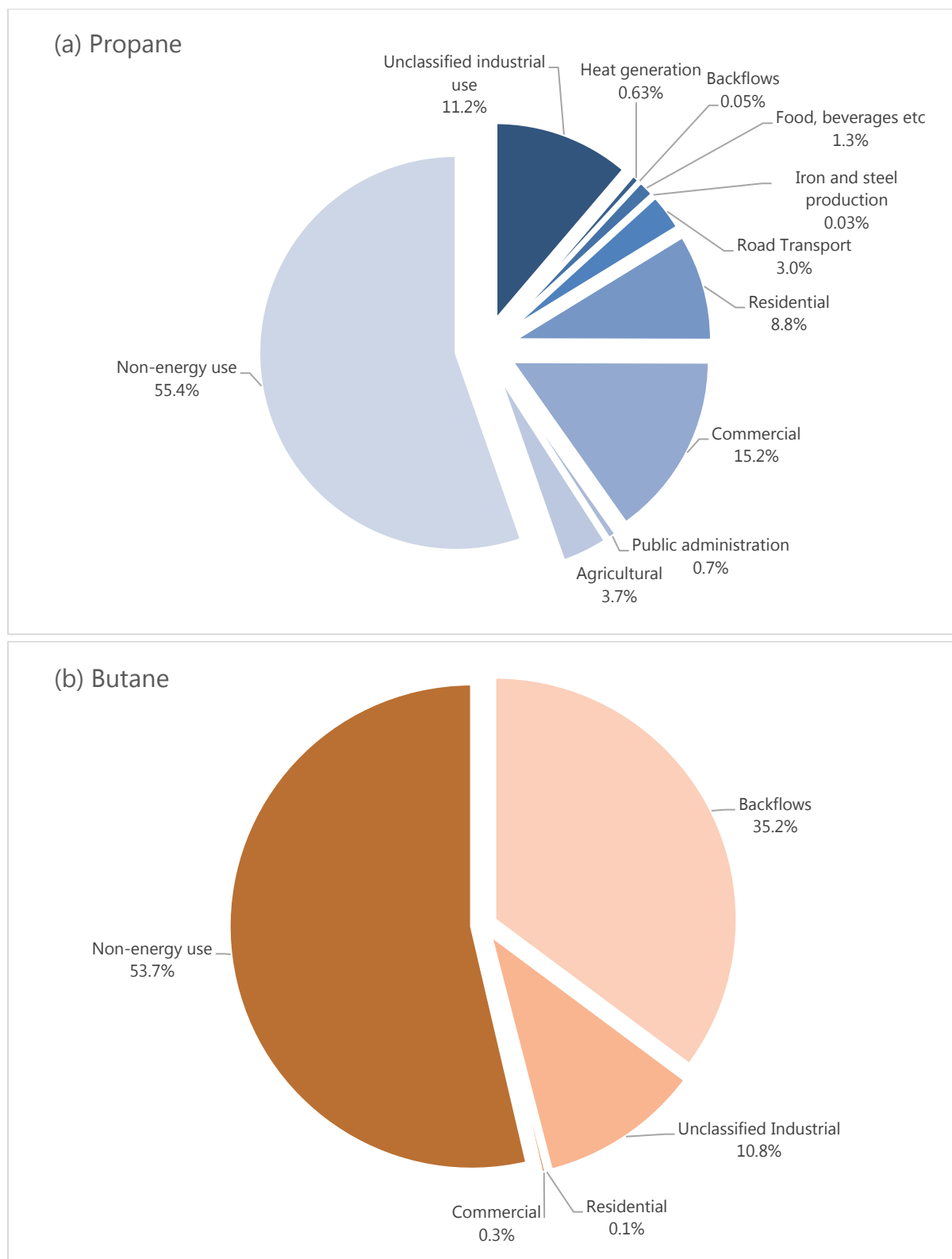


Figure 2. Full breakdown of UK propane and butane demand in 2017. Source: DUKES.

Aside from industrial energy and non-energy use, the total allocations of propane use for heating in the residential, commercial and agricultural buildings sector is 28.4% and 3.0% in transport. Backflows are listed under the transformation subcategory which are deliveries from petrochemical plants back to refineries for re-processing.

The seasonal variation in monthly LPG deliveries is shown in Figure 3. The data shows that the demand for LPG does not vary significantly by season. Other fuels used for domestic and commercial heating show a strong seasonal trend such as home heating oil. Although some sources may be seasonal such as propane for domestic heating or butane for summer barbecues, the mixed variety of markets and the dominance of the petrochemical market mean that demand is reasonably well distributed throughout the year.

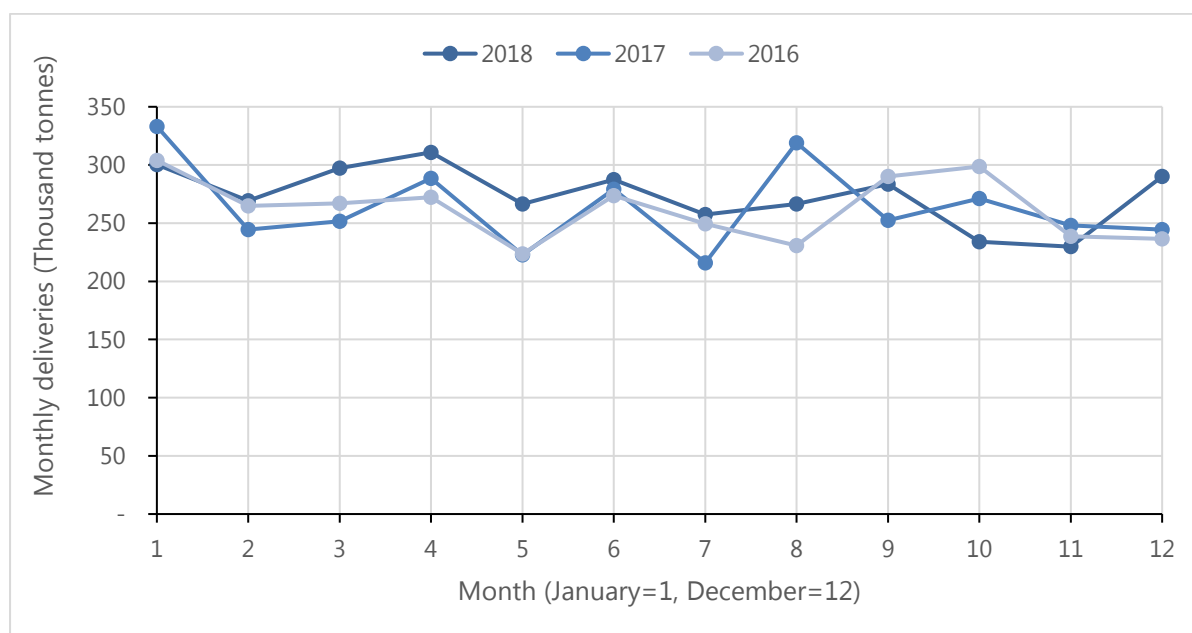


Figure 3. Monthly deliveries of propane and butane for the past 3 years. Source: BEIS Energy Trends: oil and oil products 2019.

2.2 Residential and Commercial Heating

There are currently 193,000 households in the UK using LPG for space and water heating, with a further 200,000 households using solid fuels and 1.1 million households using kerosene heating oil. The distribution of properties off the gas-grid is widespread across the UK typically in rural areas with high densities in Scotland, Wales the North of England, East Anglia and the South West (Figure 4).

Propane consumption in the domestic sector was 199,000 tonnes in 2017, with a further 16,000 tonnes used in public administration buildings, 344,000 tonnes used in commercial buildings and 85,000 tonnes in agriculture. The total current opportunity for residential and commercial heating is therefore estimated at 644,000 tonnes.

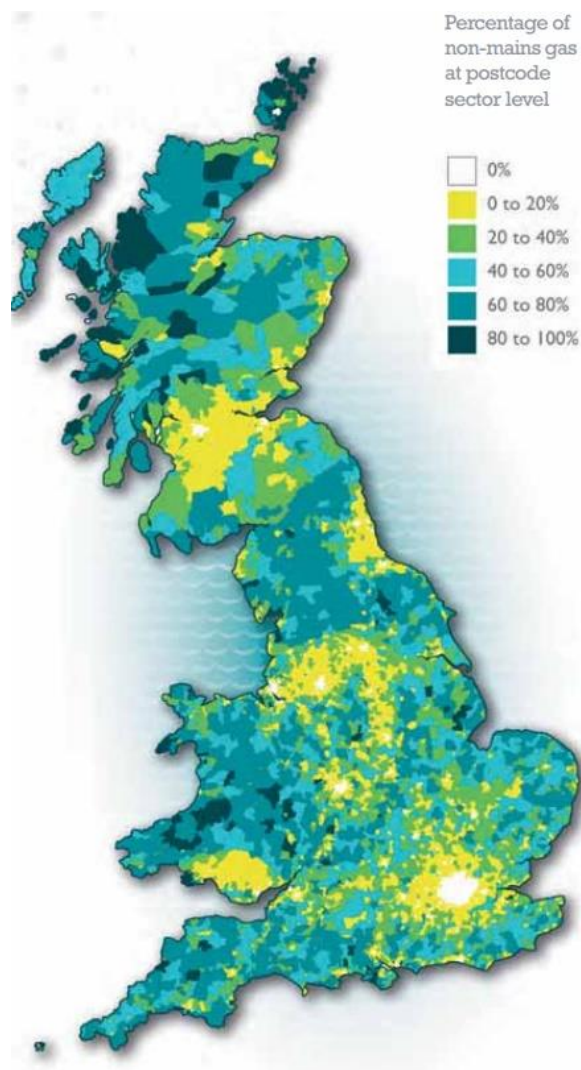


Figure 4. Map of off-gas grid properties in the UK. Source: Liquid Gas UK

2.2.1 Relevant Policies

Temperature-adjusted greenhouse gas emissions from the buildings sector increased for the second consecutive year in 2017 and less than 5% of heat generated was from renewable sources. The decarbonisation of heat is therefore one of the greatest challenges in climate change mitigation in the UK. Emissions from heat account for 37% of national emissions and despite efforts to incentivise renewable heating technologies, decarbonisation of the heat sector has been relatively slow (BEIS, 2018)¹.

In order to meet the target of 80% reduction in greenhouse gas emissions by 2050, the Government is supporting low carbon heating fuels and technologies through the Renewable Heat Incentive (RHI). Under both the domestic and non-domestic RHI, off-gas grid properties and businesses have received the highest levels of support in order to move away from fossil fuels including LPG, heating oil, gas oil,

¹ BEIS (2018) Clean Growth – Transforming Heat
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/766109/decarbonising-heating.pdf

coal & smokeless fuel. The future of the RHI scheme is under review at the current time, but support for low carbon heating technologies is expected to continue beyond 2021.

The UK is not currently on track to meet the fourth and fifth carbon budgets laid out under the Climate Change Act and in a response the consultation *A Future Framework for Heat in Buildings*², the Government made clear that through the Clean Growth Strategy the UK is committed to phase out the installation of high carbon fossil fuel heating in new and existing buildings during the 2020s. In addition, all new homes built after 2025 will be required to have a low-carbon heating system and will not be connected to the national gas grid.

For the Government to meet its goal of net zero emissions by 2050, radical reforms are needed in the heat sector. In its publication *UK housing: Fit for the future?*, the Committee on Climate Change (CCC) recommended that the Government develop a roadmap for decarbonising heat within the next three years, prioritising heat pumps and hybrid systems in off-gas grid properties. However, it is widely recognised that a proportion of off-gas grid homes are not suitable for electrification, though estimates vary. Biopropane has the key advantage of being able to be used directly in boilers with no modifications required to the heating system or radiators.

The CCC has recognised the benefits of biopropane; in its technical report on achieving net zero, biopropane was used as the model fuel for hybrid heat pump systems in properties not suitable for full electrification (CCC, 2019). Under their Further Ambition scenario, this equates to around 4.75 million hybrid heat pumps using a combination of hydrogen and biopropane with the latter totalling 7 TWh (requiring around 550,000 tonnes). The REA Bioenergy Strategy 2019 also sets out future scenarios for LPG and biopropane. The LPG for heat market is expected to grow to 42 PJ by 2032 (requiring approximately 923,000 tonnes assuming CV of 45.5 PJ/MT). A 70% market share for biopropane is considered realistic, equating to 29 PJ (requiring 625,000 tonnes assuming CV of 46.4 MJ/kg).

National Grid also present several scenarios and consider biopropane in the future heating fuel mix in its latest Future Energy Scenarios publication (National Grid, 2019). Rather than stating a total energy demand for biopropane, these scenarios consider the total number of installed biopropane heating systems, ranging from 150k to 1.5 million by 2050.

One of the key recommendations in the CCC's publication *Biomass in a Low-Carbon Economy*, was to ensure biomass is used in the most effective way, including gasification technologies for the transport and heat sectors. It goes on to suggest that the UK could access enough sustainable biomass to provide between 5% and 15% of primary energy demand in 2050. It is possible that biopropane could be a key component of the future bioenergy mix, given the right incentives and consumer awareness.

2.2.2 Opportunity

The potential market opportunity in this sector may increase if there is some incentive or clear Government direction for households to switch from heating oil or solid fuel to LPG or biopropane. LPG has the lowest greenhouse gas and air pollution emissions of any fossil fuel heating system and therefore there may be a case to incentivise more households to install LPG heating systems. Such a

² <https://www.gov.uk/government/consultations/a-future-framework-for-heat-in-buildings-call-for-evidence>

switch is unlikely to require significant changes to the central heating system and radiators as would be required in the installation of heat pump. Although a new boiler, tank and fuel supply lines would be required if switching from heating oil, installation of a new biopropane system is likely to be less intrusive, as shown in Table 1.

Table 1. Overview of requirements to switch off-gas grid heating systems

Existing System	New Heating System	Requirements
Heating oil/solid fuel	Biopropane	<ul style="list-style-type: none"> • New boiler (commercially available high efficiency gas/LPG combi condensing) • Modified fuel supply lines • New tank (at no extra cost to consumer since LPG tanks are owned by the supplier)
Heating oil/solid fuel	Heat pump	<ul style="list-style-type: none"> • New heat pump system (extensive earthworks if ground source) • Insulation upgrades to the property • Replacement of radiators & pipes • Possible underfloor heating • Installation of hot water cylinder • Replacement of 'power showers' with electric
Heating oil/solid fuel	Hybrid heat pump (with biopropane)	<ul style="list-style-type: none"> • As above, but with extra cost of boiler & tank replacement
LPG	Biopropane	<ul style="list-style-type: none"> • Fuel switch

Biopropane is not currently eligible for RHI payments and the CCC has recommended that the Government prioritises heat pumps and hybrid systems for future support. However, a proportion of rural off-gas grid dwellings are not currently suitable for electrification through the installation of heat pumps and biopropane may appeal to those consumers with existing LPG boilers (BEIS, 2018). Estimates of the proportion of homes that are not suitable for electrification range from 9% (technically suitable) to 16% (at current levels of insulation), although the figure could be as high as 59% (Myers et al., 2018). Evidently, the 193,000 households which currently have an LPG boiler could be very quickly converted to biopropane with no extra capital expense to the homeowner, as soon as sufficient fuel is available.

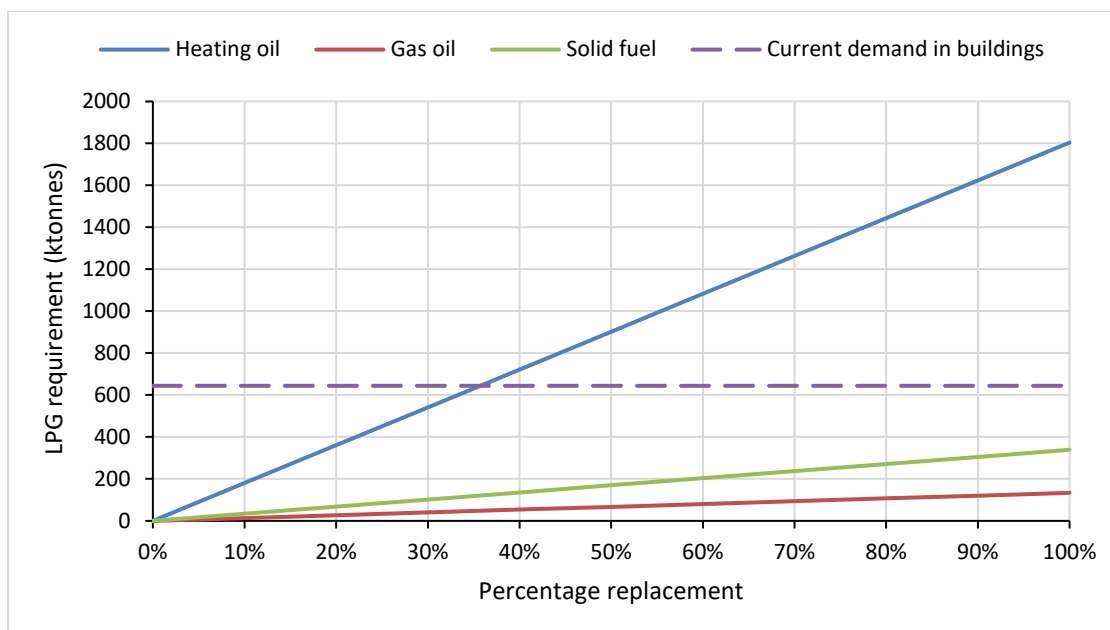


Figure 5. Potential LPG requirements if households heated by heating oil, gas oil and solid fuel were to switch to LPG at different replacement rates.

In domestic, public and commercial buildings, LPG is stored in pressurised vessels and used for space and water heating in areas that do not have access to the national gas grid. LPG is versatile and can be stored for long periods without oxidation or degradation. In agriculture, LPG may be used for crop drying or for the heating of poultry houses or horticultural buildings.

Biopropane may also be used in micro-combined heat and power (microCHP) fuel cells. Appliances developed such as the Viessman Vitocalor or the SOLIDpower BlueGEN are highly efficient and fuel flexible, able to be powered by natural gas, hydrogen or biopropane. Additionally, a strategic partnership was announced in 2018 between Bosch and Ceres Power; a leading UK manufacturer of fuel cells.

2.2.3 Impact Assessment

LPG is a gas at the point of combustion and therefore emissions of air pollutants are lower than heating oil and solid fuel, as shown in Table 2. In comparison to kerosene heating oil, emissions of PM_{2.5}, NO_x and SO₂ can be reduced by 41%, 7% and 95% respectively by using LPG. The lifecycle GHG emissions of fossil LPG are also 19% lower than heating oil, although 15% higher than natural gas.

Table 2. Comparison of emission factors for different residential heating fuels according to the NAEI (2016 values).

Pollutant	Emission factor (g/MWh)					
	Kerosene	LPG	Gas oil	Coal	Natural gas	Electricity
PM _{2.5}	6.8	4.0	6.8	1,146	3.8	-
NO _x	184	171	184	448	65	-
SO ₂	23.5	1.0	29.2	2,925	0.96	-
CO ₂ e* (kg/MWh)	298	241	278	395	210	233

* Values derived from SAP 10.0

Emissions of PM_{2.5}, NO_x and SO₂ from biopropane heating systems are expected to be the same as for fossil LPG, although the lifecycle GHG emissions are reduced.

A review of the carbon footprint of biopropane derived from Hydrotreated Vegetable Oil (HVO) (see section 4.1.1) was carried out by Johnson (2017). It found that the lifecycle GHG emissions of biopropane are highly variable depending on feedstock and process conditions, ranging from 18 gCO₂e/kWh to 367 g CO₂e/kWh. Biopropane produced from feedstocks such as tallow and waste oils have the lowest lifecycle GHG emissions, while feedstocks such as rapeseed or soybean oil have the highest GHG emissions. The hydrogen source is also a key variable in the production of HVO biopropane. Most hydrogen is currently produced from the steam reforming of methane but some HVO plants such as SkyNRG in the Netherlands plan to use hydrogen produced from the electrolysis of water using renewable energy, which would have a significantly lower carbon footprint.

As with all biofuels, biopropane is currently more expensive than its fossil fuel equivalent. In the transport sector, this is overcome by a lower fuel duty rate and renewable transport fuel incentives. However, such incentives are not currently available for biopropane in the heat sector and as such, the impact of fuel switching on consumer bills and fuel poverty will need to be considered.

By streamlining and diversifying production processes, industry estimates that biopropane could be produced cost competitively with fossil LPG without subsidy by 2030 (Cornell and Osborne, 2018). 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 and protect those most vulnerable to heating fuel price increases.

2.3 Residential and Commercial Cooking

LPG for cooking has gained a lot of interest in developing countries where LPG cookstoves offer a safer and cleaner energy source than cooking on an open fire using solid fuel. A very large-scale subsidised project in Indonesia converted over 50 million households from kerosene to LPG for cooking in just 5 years and reported reductions in greenhouse gas emissions of 31% compared to 2007 (Thoday et al., 2018). NO_x emissions were said to have reduced by 13% and SO₂ by 90%, despite an increase in the population over the same time period. Similar social and health benefits have been observed in Brazil and India (Goldemberg et al., 2018).

In the UK, significant volumes of propane and butane are consumed in off-gas grid cooker hobs, by street food vendors and for outdoor cooking; examples of which include holiday parks, mobile catering and domestic barbecues. Here propane and butane are supplied in refillable cylinders ranging in size from 4 kg to 47 kg, coloured red for propane and blue for butane. Butane has a 17.5% higher calorific value than propane on a volume basis, but it has a significantly higher boiling point of -2°C compared to -42°C for propane. Butane is therefore most commonly used in indoor applications such as cooking burners or portable gas heaters, whereas propane is most commonly used in commercial applications. A third option, patio gas, is used for patio heaters in households and restaurants. Bio-based isobutene used for this purpose is commercially available in France through a partnership between Butagaz and Glogal Bioenergies.

2.3.1 Relevant Policies

There are no specific policies aimed at reducing emissions from the cooking sector in the UK, but it is a major consumer of natural gas, LPG and in some cases kerosene in combined cooking and heating appliances such as AGA's.

2.3.2 Opportunity

Properties that have a connection to the national gas grid are likely to use a combination of gas and electric hobs and are therefore unlikely to adopt LPG, except for in domestic barbecues. The proportion of off-gas grid properties using bottled LPG for cooking hobs is unknown, though some homeowners may prefer gas cooking hobs to electric.

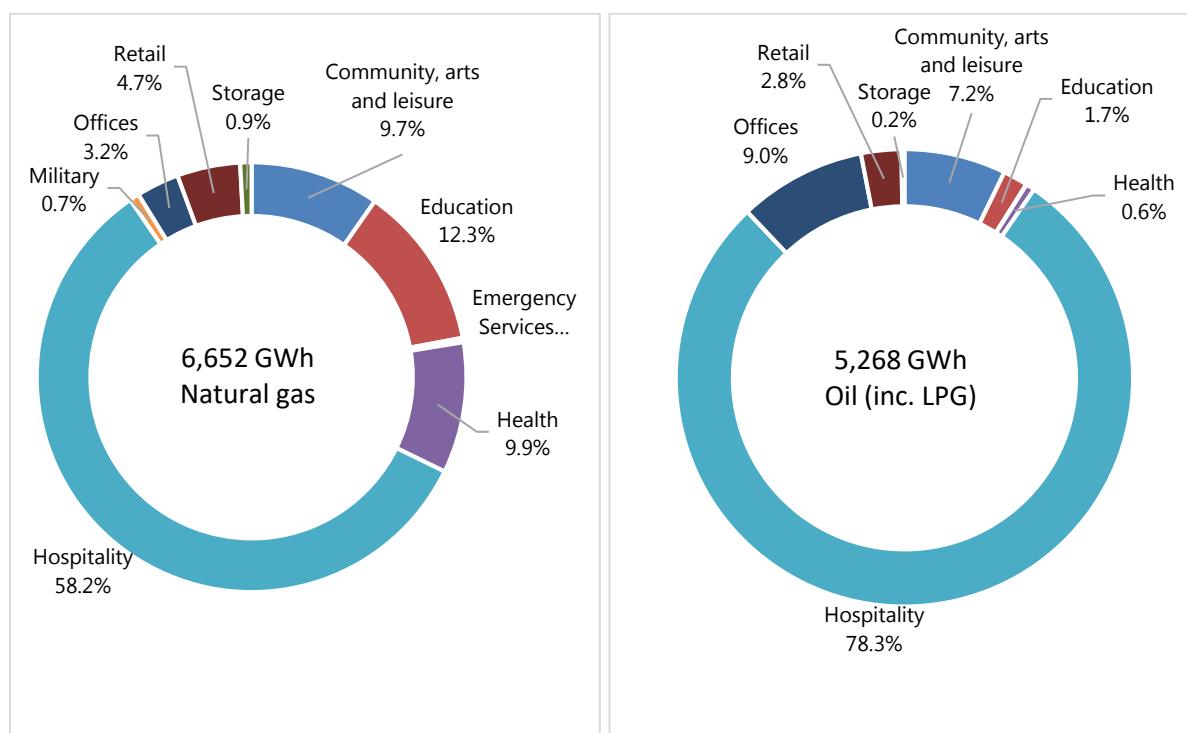


Figure 6. Breakdown by end use of natural gas and oil demand for catering. Data source: ECUK

According to ECUK (2018), domestic energy consumption for cooking was 13,665 GWh in 2017, of which 56% was derived from gas and 44% was derived from electricity. The breakdown of energy used for catering in different commercial sectors is shown in Figure 6. A large amount of oil is consumed in the hospitality sector, though the definitions used in ECUK mean that 'oil' may include liquid fossil fuel oils as well as LPG and other fuels. There may therefore be an opportunity for biopropane in this sector of up to 5,268 GWh to replace fossil LPG or other oil-based fuels in the catering sector.

The total opportunity for biopropane in the residential and commercial cooking sector is therefore estimated to be between 5 TWh and 10 TWh (equivalent to 392-784 kilotonnes).

2.3.3 Impact assessment

Cooking with a gas flame is preferred over electric hobs by many homeowners and commercial kitchens. There are limited opportunities for cooking with hydrogen or biomethane in off-gas grid applications due to difficulties with storage and therefore biopropane would be an ideal candidate to replace fossil LPG in these instances. There may also be a marketing opportunity to target restaurants seeking to reduce their carbon footprint through corporate social responsibility. The restaurant's GHG are likely to be reduced and air pollutant emissions will be unaffected compared to fossil LPG.

Approximately 88,000 tonnes of charcoal were consumed in the residential sector in 2017, equivalent to 57,000 tonnes of LPG. Summer barbecues can be a significant source of local air pollution when using charcoal and air quality improvements may be achieved by fuel switching to LPG or biopropane. According to Johnson (2009), the carbon footprint of charcoal grilling is almost three times larger than that of LPG grilling so reductions in GHG emissions may also be achieved. Additionally, most charcoal consumed in the UK is imported from regions such as South America and Sub-Saharan Africa where there are concerns over deforestation, although the fraction which is sustainably sourced is unknown.

2.4 Transport

LPG is used as a fuel in a range of transport applications including road vehicles, forklift trucks, ships and aircraft. Specific opportunities and relevant policies are described in the relevant sub-sections below.

2.4.1 Shipping

According to the Canal and Rivers Trust, there are approximately 34,000 boats and narrow boats on UK waterways, 26% of which are used as primary residences. Here LPG is the most common fuel used for cooking and also for space & water heating. A guide produced by WLPGA (2017) estimates that usage in these vessels is relatively low, with a 15kg cylinder typically lasting several days.

There is also a growing demand for low emission fuels in the shipping sector, both in terms of greenhouse gases and air pollutants. Combined domestic and international shipping emissions have reduced since 1990, but not markedly (CCC, 2018), and therefore there is a growing need for low-emission ships. Historically the shipping sector has been one of the least regulated sources of air pollutants, with high emission factors for particulate matter and sulphur dioxide from the burning of diesel and fuel oil. Projections by the Air Quality Expert Group (AQEG, 2017) show that in 2020 shipping emissions could contribute 14% of SO₂ emissions and 21% of primary PM_{2.5} emissions in the UK. Following the implementation of legislation on the maximum sulphur content in shipping fuel in 2006/7, there was a marked reduction (nearly 50%) in SO₂ levels at ports in the English Channel. This demonstrates the impacts that fuel switching to low emission alternatives can have on ambient air quality.

In April 2018, the International Maritime Organisation (IMO) adopted a resolution to reduce greenhouse gas emissions from shipping by at least 50% by 2050 compared to 2008 levels. The CCC has recommended that international shipping emissions also be included in carbon budgets.

2.4.2 Aviation

LPG is rarely used in aviation but is included here mainly due to the importance of this sector's growing demand for sustainable aviation fuel, which may impact on other sectors. A small number of aircraft in the UK have spark ignition engines fuelled by aviation gasoline (Avgas). It may be possible for these aircraft to be converted to run on LPG but Avgas contains a number of additives that are not typically present in road vehicle gasoline and therefore conversion may not be possible or straightforward.

Several technologies for the production of sustainable aviation fuels may produce biopropane as a co-product. One example is hydroprocessed esters and fatty acids (HEFA) which is similar to HVO and produced via the hydrotreating of oily biomass feedstocks such as vegetable oils and used cooking oils. The aviation industry has grown rapidly in recent years and is forecast to continue to do so. Decarbonisation targets for this sector include a cap on net CO₂ emissions from 2020 (carbon-neutral growth) and a reduction of 50% of GHG emissions by 2050 relative to 2005 levels. Hence growing demand for fuels like HEFA may benefit the biopropane industry.

A recent Government consultation 'Aviation 2050 – the future of UK aviation'³ sought feedback on proposals for a new aviation strategy. The strategy will set out the challenges and opportunities for aviation to 2050 and beyond and will emphasise the significance of aviation to the UK economy and regional growth, as well as the importance of developing a partnership for sustainable growth which meets rising passenger demand, balanced with action to reduce environmental and community impacts. The UK Aviation Strategy is due to be published later in 2019.

2.4.3 Road vehicles

There are estimated to be between 120,000 and 170,000 vehicles in the UK using LPG as fuel, also known as Autogas. It is available to buy from approximately 1,200 refuelling stations nationwide, which equates to around 16% of total refuelling stations. According to DUKES, 68,000 tonnes of propane was consumed in the transport sector in 2017, accounting for 3% of total demand.

Biopropane has recently been introduced to the road transport market in the UK by one supplier; it is initially being sold at small volumes, at a 40% blend with fossil LPG.

³ <https://www.gov.uk/government/consultations/aviation-2050-the-future-of-uk-aviation>

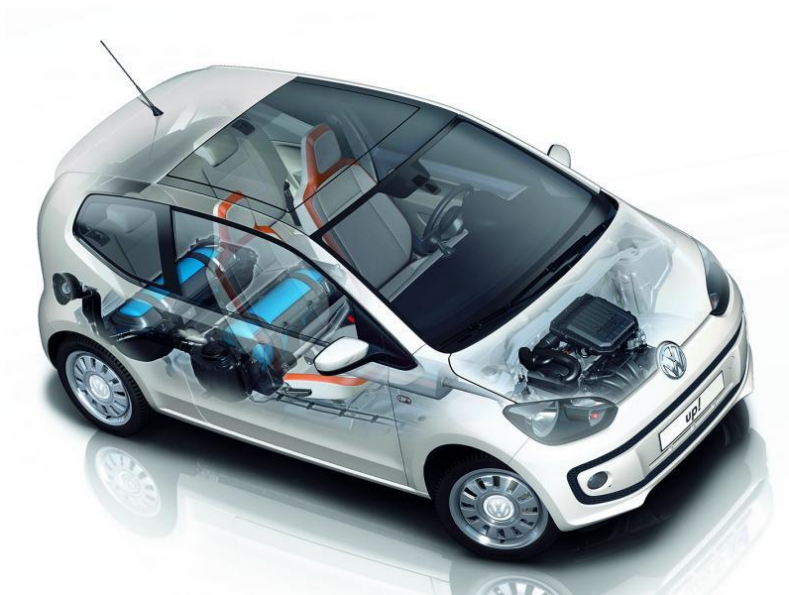


Figure 7. An example of a passenger car converted to LPG. Image source: Autocar

Most spark ignition petrol cars can be converted to LPG, allowing them to use both petrol and LPG on a 'dual fuel' or 'bi-fuel' basis. The cost of conversion is estimated to be around £2,000 but significant savings can be made on the fuel price. The average price of LPG in the UK in June 2019 was 59 pence per litre for LPG compared to 128 pence per litre for petrol and 132 pence per litre for diesel.

GHG emissions savings can also be achieved by converting to LPG. The well-to-wheel CO₂ emissions factor for a biopropane vehicle was estimated to be 23 g/km, allowing significant savings to be made against petrol (201 g/km), diesel (159 g/km) and fossil-LPG (156 g/km) (Element Energy, 2018). Major reductions can also be achieved in the emission of air pollutants such as particulate matter (PM) and oxides of nitrogen (NO_x). Air quality policies are a major market driver for low-emission vehicles and there is evidence to demonstrate that uptake of LPG vehicles could significantly reduce emissions in urban environments (see Table 3).

Table 3. Examples of LPG use in UK road vehicles

Vehicle type	Location	Details
Black taxi cabs	Birmingham	65 Hackney carriages (black cabs) were converted from diesel to LPG in 2015/16. Achieved emission reductions of 95% for NO _x and 97% for PM (Element Energy, 2016).
Black taxi cabs	London	In February 2019, the Mayor of London Sadiq Khan announced plans to invest £24m to help reduce emissions from the capital's black cabs, with a focus on electric vehicles. £5m is also available to help Euro 5 taxis convert to LPG, which can reduce NO _x emissions by 70% and running costs by £200 per month (Mayor of London Office, 2019).

LPG has also attracted interest for use in heavy goods vehicles (HGVs) due to the emissions reduction potential against petrol and diesel as well as the limited range of battery technologies. 2- to 16-cylinder diesel engines may be hybridised with LPG (as well as CNG or LNG) through the retrofitting of an LPG-diesel kit such as the STAG diesel or the Mercury Quicksilver AFI. There is some evidence to suggest that LPG–diesel dual fuel engines can reduce fuel consumption, PM and NO_x emissions but to

what extent is not clear at the current time (Ashok et al., 2015). Nobel Foods based in Newark-on-Trent has upgraded 50 articulated trucks to LPG-diesel dual fuel, reportedly saving 14% on fuel bills and 6% on CO₂ emissions.

Biopropane can also act as a range extender for hybrid electric vehicles. For example, the Dutch firm Emoss has developed an electric HGV fitted with a 120-litre tank for LPG or CNG which is used to power an electric generator and charge the batteries. This feature is said to increase battery-only range from 40 to 250 miles and can be switched off when the vehicle enters an ultra-low emission zone (LCVP, 2018). Furthermore, biopropane could be used to power on board fuel cells to again increase range.

Relevant Policies

Road transport is a major contributor to the UK's greenhouse gas and air pollutant emissions and there are numerous policies aimed at decarbonising this sector and promoting the uptake of low and ultra-low emission vehicles (ULEVs). ULEVs are defined as vehicles which emit less than 75 g CO₂/km and are capable of travelling 10 miles with zero emissions. These are typically battery-only-, plug-in hybrid-, range-extended- or hydrogen fuel cell electric vehicles.

The Road to Zero Strategy (DfT, 2018) states that although fossil-LPG vehicles have similar well-to-wheel GHG emissions to diesel equivalents, their lower air pollutant emissions may be a good current alternative to diesel in urban driving conditions. Switching to biopropane may therefore reduce both GHG and air pollutant emissions compared to diesel. Under the Renewable Transport Fuel Obligation (RTFO), bio-LPG receives 1.75 RTFCs per kg whereas biomethane receives 1.9 RTFCs per kg. LPG as a road transport fuel is also incentivised through a lower fuel duty of 31.61 pence per kilogram compared to 57.95 pence per litre for petrol, diesel, biodiesel and bioethanol. The fuel duty for natural gas and biogas is lower still at 24.7 pence per kilogram (please note the difference in units). The Government announced in 2018 that the fuel duty escalator would end for LPG, in an effort to encourage uptake of low emission vehicles (DfT, 2018); however, fuel duty has been frozen for nine consecutive years. Biopropane is also approved under the International Sustainability and Carbon Certification scheme (ISCC). Under the Fuel Quality Directive 2009/30/EC, the UK is required to reduce the greenhouse gas intensity of transport fuels by at least 6% by 2020 relative to 2010 levels. LPG and biopropane are key fuels which can help achieve this.

More recently there have been renewed efforts to reduce PM and NO_x emissions from road transport, which was highlighted as the largest source of NO₂ in the 2019 Clean Air Strategy. As a result, from 2040 there will be a ban on all new petrol and diesel cars and vans under the Government's *Plan for Tackling Roadside Nitrogen Dioxide Concentrations*. In addition, the Government has mandated that six UK cities implement a Clean Air Zone (CAZ) by 2020 in order to improve air quality; these are Birmingham, London, Leeds, Nottingham, Derby and Southampton. A further 23 local authorities have been identified which must carry out a feasibility study to establish whether or not a Clean Air Zone is required. In some cases, drivers will be charged for moving within a CAZ if their vehicle does not meet the local emissions standards. This has been taken further in Central London where an Ultra-Low Emission Zone (ULEZ) is in force whereby older more polluting vehicles must pay a charge of £12.50 per day for light vehicles and £100 per day for heavy vehicles.

2.4.4 Non-road vehicles

Forklift trucks are used in warehouses for the movement of stock and are typically fuelled by diesel, petrol, LPG and electricity. There is interest in their emissions from point of view of warehouse air quality and of the lifecycle analysis of goods. According to the British Industrial Truck Association (BITA, 2019), an estimated 35,300 forklift trucks were sold in the UK in 2018. In total, 38% of forklift trucks within Europe are powered by LPG whereas 49% are electric and 14% are diesel (Atlantic Consulting, 2018).

Other potential applications of biopropane include agricultural irrigation systems and machinery, construction equipment, mining equipment and generators.

2.4.5 Impact assessment

The average greenhouse gas emissions factor for an LPG car is 171 gCO₂e per kilometre (a reduction of 19% relative to petrol) (DfT, 2018). This is slightly higher than compressed natural gas at 158-164 gCO₂e per kilometre.

Particulate matter (PM) emissions for a Euro 6 medium car are 1.3 milligrams per km for an LPG car which is the same as CNG, but 32% lower than diesel and 19% lower than petrol. Since biopropane is a drop-in replacement for fossil LPG, the PM emissions factors are the same.

NO_x emissions for a Euro 6 passenger car fuelled by LPG are 56 mg/km, compared to 450 mg/km for a medium diesel car and 61 mg/km for a medium petrol car (EMEP/EEA, 2018)

Element Energy (2018) estimated that there is a potential market size of between 2000 and 260,000 for small commercial vans to be converted to LPG in areas where NO_x limits are exceeded. This could save up to 2,400 tonnes of NO_x, 23 tonnes of PM and 0.8 tonnes of GHGs per year relative to diesel.

2.5 Industrial Process Use and Chemicals

The industrial sector is the single largest consumer of propane and butane in the UK, accounting for almost two thirds of consumption. Substantial volumes are delivered to the petrochemical industry as a feedstock for the manufacturing of plastics, synthetic fibres and other products. Direct industrial uses include soldering, heat treatment and cutting as well as for process heat and power. Butane is the principal component of lighter fluid and approximately 1.6 billion lighters are sold every year in Europe.

Ethane, propane and butane are used in the petrochemical industry for the production of olefins which are unsaturated hydrocarbons (alkenes) that are important building block chemicals. Examples include ethylene, propylene and isobutene which are produced by thermal or steam cracking of naphtha. These compounds are used in a range of industrial products and process, including plastics.

Ethylene is used in the production of several common materials including low density- and high density- polyethylene (LDPE, HDPE), polyethylene terephthalate (PET) and polystyrene, and polyvinyl chloride (PVC). It is also used in the manufacture of industrial alcohol (ethanol), acetaldehyde and ethyl acetate.

Propylene is used to manufacture a wide range of chemical and materials including the manufacture of polypropylene, a common light weight and durable thermoplastic used in a variety of applications including packaging, textiles, carpets, furniture and appliances. Other propylene derivatives include acrylic acid, phenol and propylene glycol which is used in the manufacture of polyesters and as a base for antifreeze and de-icers.

Isobutene is formed by steam cracking naphtha or LPG, through the isomerisation or catalytic dehydrogenation of butane. It is used for the production of octanes which are components of petrol/gasoline, as well as in the manufacturer of butyl rubber which is a synthetic rubber valued as a durable liner in tyres and other applications. An overview of the market for isobutene is given in Figure 8.

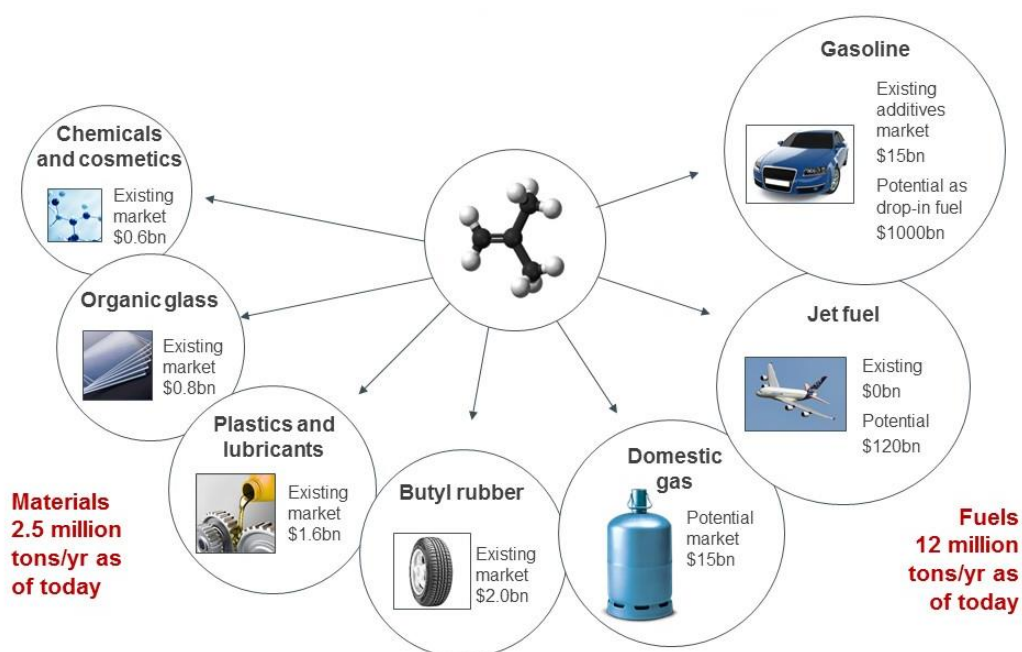


Figure 8. Key markets for isobutene. Source: Global Bioenergies⁴

2.5.1 Opportunity for biopropane

As the largest end user of LPG products, the industrial sector is an important potential market for biopropane. In 2017, UK industry consumed 285,000 tonnes of propane and 80,000 tonnes of butane for process energy use, but this was greatly exceeded by non-energy use where a further 1,234,000 tonnes of ethane, 1,255,000 tonnes of propane and 400,000 tonnes of butane was consumed (DUKES, 2018).

Whilst it is possible that some of the fossil-LPG used in the petrochemical industry could be replaced with biopropane or bio-based isobutene, there is little incentive for manufacturers to do so at the current time. However, there is increasing market potential for the production of bio-based plastics through this route, which is a rapidly growing sector (Crippa et al., 2019) and such applications could

⁴ <https://www.global-bioenergies.com/group/isobutene-process/?lang=en>

attract higher values than the energy market due to the inherently higher end product value thus increasing demand.

Neste and LyondellBasell announced in June 2019 a collaboration to produce bio-based polyethylene and bio-based polypropylene at a commercial scale⁵. Neste has also announced a partnership with IKEA to produce bio-based PE and PP commercially, with IKEA aiming to use wholly recycled or renewable materials in its products by 2030⁶.

Since biopropane and bio-isobutene are drop-in replacements for their fossil fuel equivalents, they could be introduced into the industrial supply chain with relative ease and at increasing amounts as more product becomes available.

2.6 Biomethane spiking for grid injection

Natural gas flowing in the UK grid typically contains around 90% methane and has a calorific value in the range 37.5 to 43.0 MJ per m³. The net calorific value of methane is 36 MJ per m³ and therefore when biomethane is injected into the grid from anaerobic digestion plants, it must be enriched with gas of a higher calorific value in order for the CV of the natural gas mix in the grid to be maintained. This is typically achieved by blending in propane which has a CV of 86 MJ per m³ as a gas and 23,500 MJ per m³ when compressed into liquid form. LPG is typically blended at a volume ratio of 3-5%.

There are currently 84 biomethane-to-grid plants operating in the UK, most of which use propane for spiking, and a map of these is provided in Figure 9. Recently there have been some cases where plants are not required to spike with propane, but this is at the discretion of the local grid operator and dependent on location, distance to nearest offtake customer, and dilution rates in the nearby grid. A 2014 report for the UK Government (Menecon Consulting, 2014) found that propane demand in this area was around 150 tonnes per year with potential to reach 5,000 tonnes per year if biomethane production were to increase to the same levels as that of larger producers such as Germany. Biopropane is not currently supported under the RHI but the future of the scheme post-2021 is under review at the time of writing.

According to RHI statistics, 2,536 GWh of biomethane was generated between May 2018 and May 2019. Based on this, the total estimated propane demand for biomethane spiking in the UK is between 15,000 tonnes and 25,000 tonnes which is significantly higher than the 2014 estimates.

There are a further 52 biomethane-to-grid projects currently under development so this propane demand could increase by more than 60% as more plants become operational. Biomethane injection is supported under the RHI and is seen as a key low carbon technology for heat decarbonisation.

⁵ <https://www.lyondellbasell.com/en/news-events/corporate--financial-news/lyondellbasell-and-neste-announce-commercial-scale-production-of-bio-based-plastic-from-renewable-materials/>

⁶ <https://www.neste.com/ikea-and-neste-take-significant-step-towards-fossil-free-future>

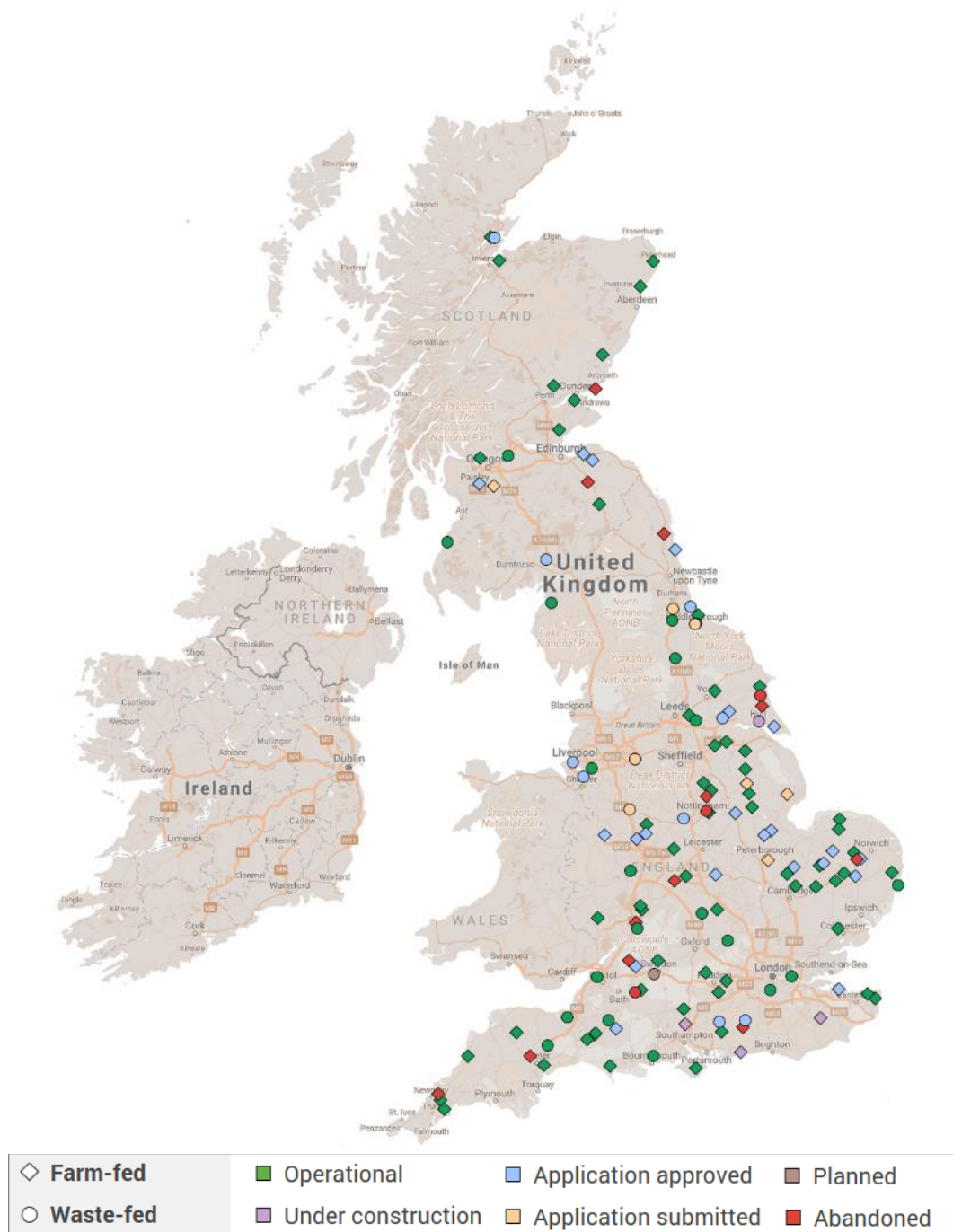


Figure 9. Map of biomethane plants in the UK. Source: NNFCC Anaerobic Digestion in the UK report 2019.

3 Supply and Distribution Overview

LPG available to buy today is either produced at UK oil refineries or imported from abroad. The UK is a net importer of propane and a net exporter of butane, although the majority of demand is currently met through indigenous production (i.e. produced at UK refineries). There are three major LPG terminals and another currently under development at Avonmouth (UKPIA, 2019), although there is a large distribution network of oil products across the country as shown in Figure 28.

Most propane consumed in the UK in 2017 was produced indigenously (1.4m tonnes), whereas around one quarter of total supply (0.56m tonnes) was imported from overseas and a further 0.47m tonnes was exported. Similarly, most butane is produced indigenously (0.78m tonnes) with just 0.22m tonnes being imported, although exports are proportionally higher than propane at 0.58m tonnes (Figure 10).

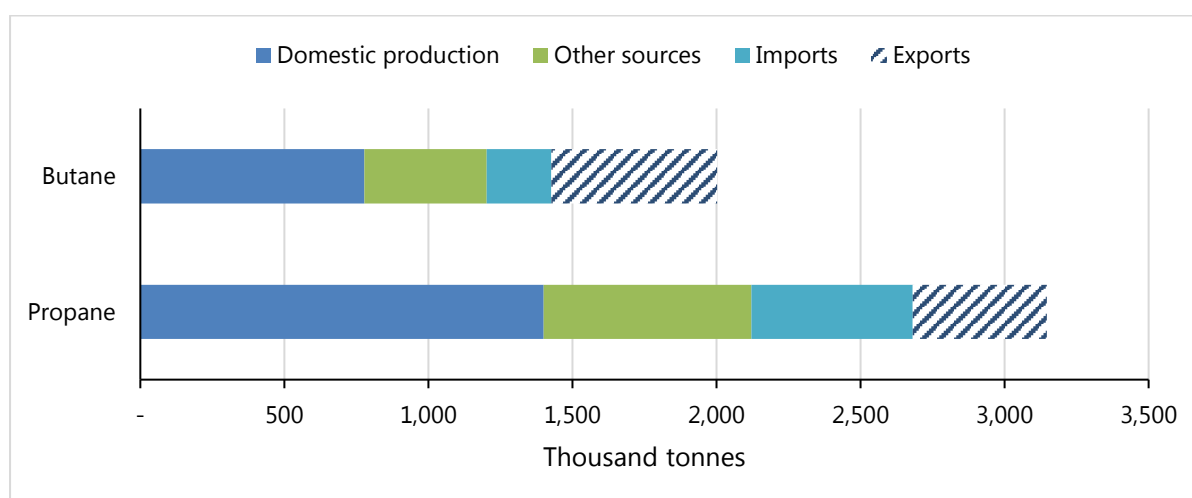


Figure 10. Production, imports and exports of propane and butane in the UK in 2017. Source: DUKES.

Two thirds of LPG currently produced in the UK is from the refining of crude oil with the remaining one third being produced from the processing of natural gas. As shown in Figure 11, the UK was the second largest producer of LPG in 2015 after Norway and was the fifth largest consumer. Due to the large and established LPG market, the UK has the potential to become a global leader in biopropane production and use across multiple sectors. There is also potential for export to Turkey, Italy, Poland and Ukraine which have mature LPG-for-transport markets, as well as in Italy, France, Spain, Turkey, Portugal and Germany where there are mature markets for LPG heating.

Given that all biopropane currently available in the UK is imported, there may be significant competition from markets in other countries which already have a greater demand for LPG for heating, cooking or for transport. Government incentives and/or LPG pricing may make the UK a more competitive market for biopropane than other countries in Europe; there is clearly an established market and supply chain for LPG throughout the UK.

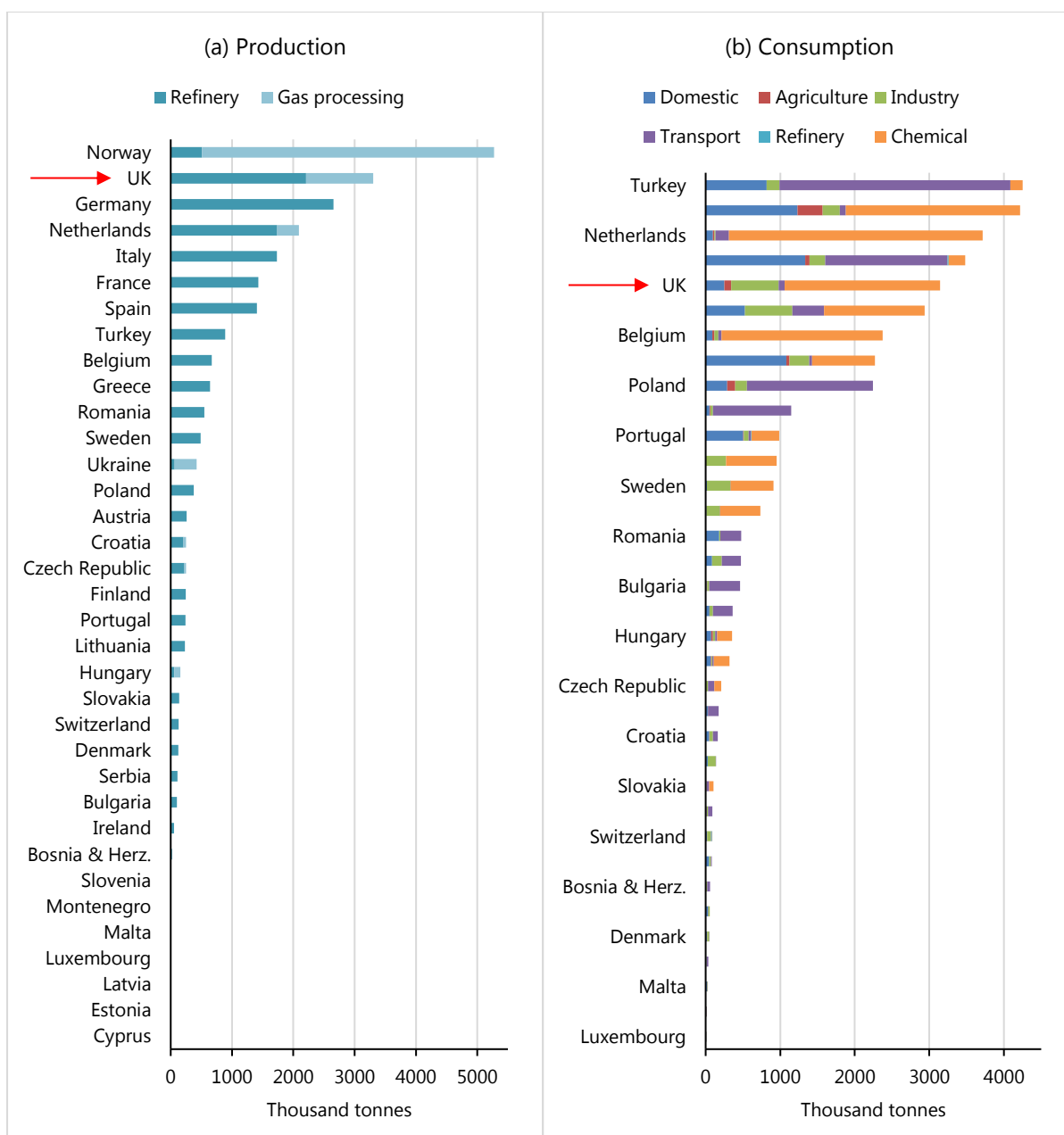


Figure 11. LPG production and consumption of European countries. Data source: AEGPL (2017)

The UK has a strong and well-established supply and distribution base for LPG to meet the needs of the residential, commercial, industrial and transport sectors. Since biopropane is a drop-in fuel, it can easily be merged into the existing supply chain or blended with fossil LPG to give a partially renewable fuel, as shown in Figure 12. There are 40-50 suppliers and distributors of LPG who are members of Liquid Gas UK; combined these cover over 98% of LPG distributed nationally. There are a mixture of larger nationwide suppliers, regional players and smaller family businesses which together have considerable experience and expertise in LPG handling and logistics. Other Liquid Gas UK member suppliers can be found on the Liquid Gas UK website⁷.

It is also now easier for residential customers to switch supplier, following the *Domestic Bulk Liquefied Petroleum Gas Market Investigation Order* which was published by the Competition Commission (now

⁷ <https://www.liquidgasuk.org/advice/supplier-search>

the Competition and Markets Authority) in October 2008 and came into effect in April 2009. The Order facilitated the rapid and simple transfer of fuel delivery and tank ownership to the homeowner's new choice of supplier.

The UK also has well-established infrastructure for the import and export of LPG, with 41 coastal and 20 inland storage terminals across the country, as shown in Figure 28. Biopropane could easily be incorporated into this supply chain without the need for additional blending equipment, tanks or racks. There are already 112 distribution depots nationwide into which biopropane products could easily be integrated.

With its robust LPG supply and distribution infrastructure, the UK has the potential to become a world leader in biopropane production and export. Both the domestic LPG market and the international LPG markets identified in Figure 11 offer significant opportunity to potential UK-based producers. Despite this, the UK is likely to remain a net importer of biopropane without local technology development and investment in indigenous production processes.

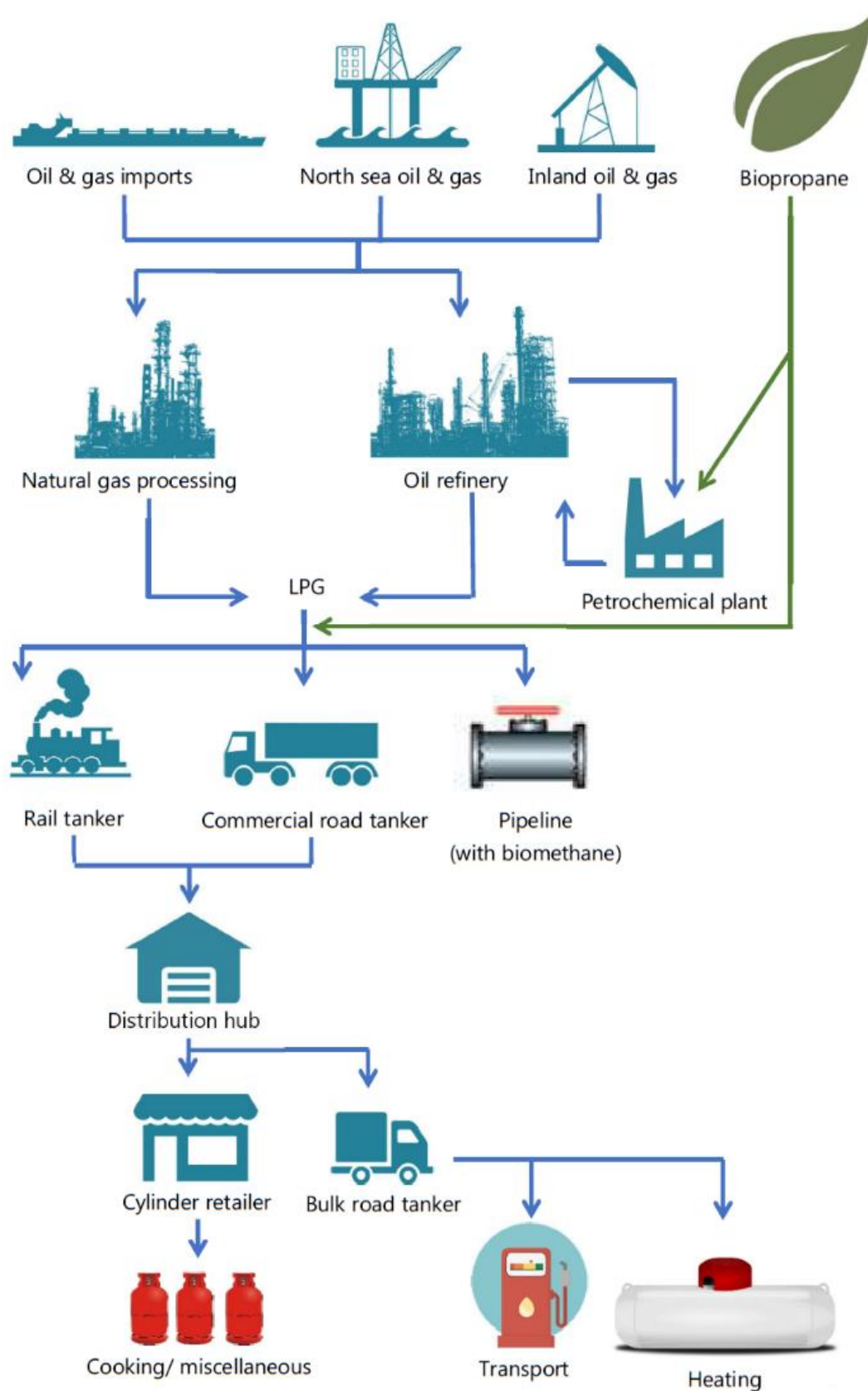


Figure 12. Integration of biopropane to the existing LPG supply chain in the UK

4 Biopropane Supply Chain Review

There are several biomass-to-energy conversion processes in which biopropane is produced as a co-product and there is a plethora of biomass feedstocks that can be used in those processes. These range from the hydrotreating of vegetable oil to produce HVO biodiesel to the production of synthetic fuels through gasification and synthesis. Currently, the primary production route for biopropane is as a co-product of HVO biodiesel where the process yields are in the range of 5-8%. Due to the large amounts of HVO biodiesel produced significant volumes of biopropane can be obtained, despite the yields being fairly low.

There are also a small number of novel processes whereby biopropane can be produced as the main target product. These include the use of specialised microbes to ferment organic wastes to produce biopropane (rather than biomethane), and also the direct synthesis of propane from the syngas produced from the gasification of woody biomass.

The EU's Renewable Energy Directive (RED) sets mandatory targets for the EU and its member states, to use increasing proportions of renewable heat, power and transport fuels in the overall energy mix. The current RED runs to 2020, setting a target of 15% renewables across the EU as a whole; this was broken down by sector in the UK's Renewable Energy Strategy (RES) to 10% of transport fuels, 14% of heat and 32% of electricity. The transport fuel requirement was transcribed into UK law through introduction of the Renewable Transport Fuel Obligation (RTFO) in 2008. Progress in meeting the RED target for transport has been slow to date and there still is a significant way to go to achieve the current 10% target.

The RED has recently been recast to set out requirements in the period 2021 - 2030, referred to as RED II, and the overall EU target for renewable energy consumption has been raised to 32% by 2030. RED II requires fuel suppliers in all member states to supply a minimum of 14% of the energy consumed in road and rail transport by 2030 from renewable sources, with each member state defining its own detailed trajectory to reach these targets. However, due to ongoing concerns about impact on land use change associated with crop-derived biofuels, the contribution of these will be capped at 2020 consumption levels within the community, and with a maximum allowable contribution of 7% towards road and rail transport in each member state, but member states are free to set lower caps than this. The UK has opted to set a crop cap of 4% on the contribution that can be made from crop-derived biofuels which after 2020 will fall linearly to 2% by 2032.

In addition, GHG saving requirements of biofuels are also tightening, a saving of at least 65% should be achieved in GHG emissions for biofuels derived from installations starting operation after 1 January 2021 compared to 60% for those that started after 5 October 2015. Therefore, a stronger focus on advanced processes, using wastes and lignocellulosic feedstocks, which typically achieve greater efficiencies and deliver greater GHG savings can be expected. As a result of future growth demands, development of such facilities is increasing and an increase in production and availability of biopropane can therefore be expected.

This chapter gives an overview of the main technologies, processes and distribution options for biopropane in the UK, which are summarised in Figure 13.

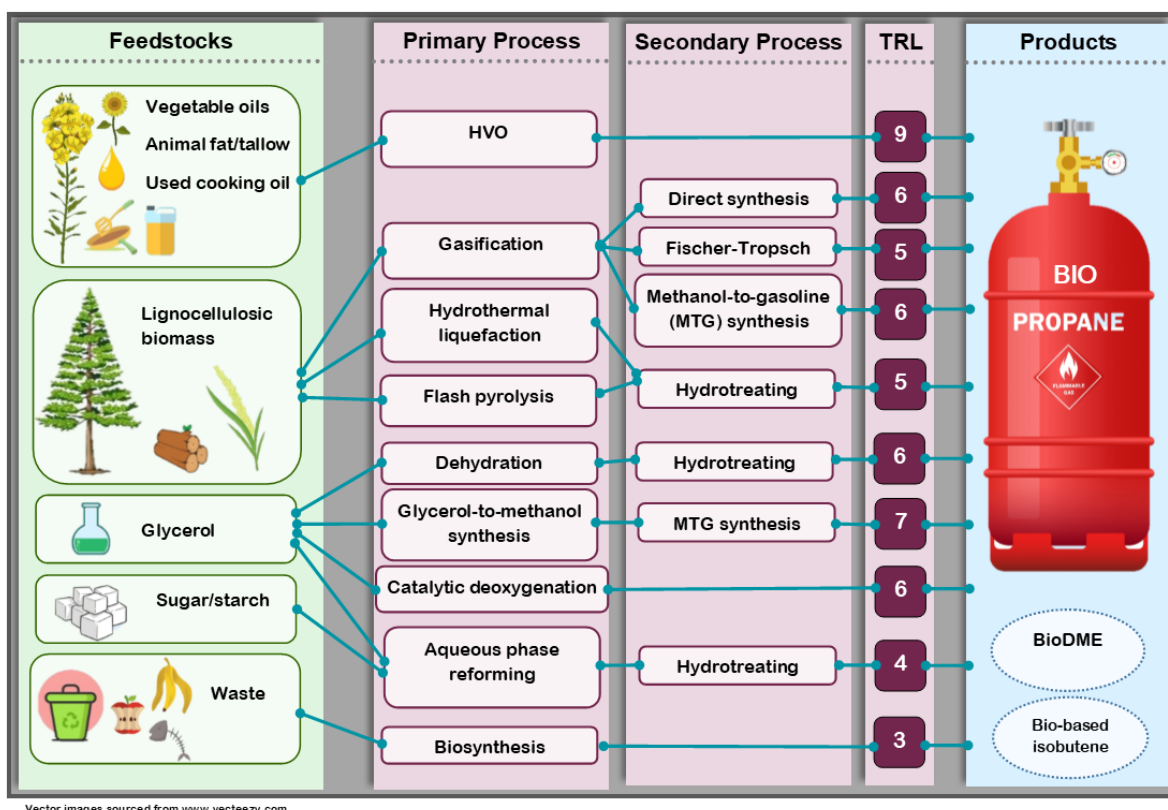


Figure 13. Overview of the feedstocks, processes and technology readiness levels (TRL) for biopropane production.

LPG mainly consists of propane and butane, but it can also include small amounts of other hydrocarbons such as propene, butene, isobutene and dimethyl ether (DME). Most processes currently target biopropane since propane is the most widely consumed component of LPG. However, as described below some feedstock and process combinations are tailored to produce the lesser known components, such as MTG synthesis for bioDME and sugar fermentation for bio-based isobutene.

4.1 Technology Review

4.1.1 Hydrotreated Vegetable Oil (HVO)

Currently the only process for the production of biopropane that is operating at the commercial scale is the hydrogenation or hydrotreating of vegetable oils, fats and biomass-derived oils. Note that for the purposes of this report, 'bio-based oil' is used as an all-encompassing term. The process involves the conversion of fatty acid feedstocks into a drop-in diesel fuel by treating the oils with hydrogen at elevated temperatures. The resulting product is known as HVO biodiesel, also known as renewable diesel and HEFA (Hydroprocessed Esters and Fatty Acids). HVO can be used directly in existing diesel engines without modification and the process can also be tailored to produce a fuel meeting the specifications for use in commercial aircraft.

Propane is produced as a by-product during hydroprocessing at a ratio of 100-111 kg per tonne of HVO biodiesel (Johnson, 2019).



Figure 14. Current and planned HVO production units⁸. Source: Greenea (2017)

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, plus a further four under construction (Figure 14). For every 100 tonnes of HVO diesel produced, around 5 tonnes of biopropane rich off gases are produced. 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, 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. 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 biopropane 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 in the EU has increased from 0.3 billion litres in 2011 to 2.8 billion litres in 2018 (Flach and Lieberz, 2018), which is expected to triple by 2025 with an average compound annual growth rate of 10% (Greenea, 2019). There are also opportunities for UK refineries to co-process bio-based oils in existing oil hydrotreaters, as described by Atlantic Consulting (2018).

⁸ This figure was produced by Greenea in March 2017 so more recent developments are not captured. For an up-to-date list of facilities, see Table 6 and 7 in Appendix.

4.1.2 Gasification with Fisher-Tropsch synthesis

Biopropane can be produced as a by-product of gasification with Fisher-Tropsch (FT) synthesis (Ail and Dasappa, 2016). A wide range of feedstocks can be used in this process including virgin and waste wood, municipal solid waste and energy crops such as miscanthus. During gasification, solid biomass materials are converted into syngas by being exposed to high temperatures in an oxygen-starved atmosphere. The syngas produced is a mixture of mostly hydrogen (H_2) and carbon monoxide (CO) which goes through a cleaning stage to remove impurities before the gas be used in FT synthesis.

The Fischer-Tropsch process was developed during the 1920s as a means of producing liquid hydrocarbon fuels from syngas using catalysts. The intermediate product is a solid mixture of hydrocarbons with around 40 carbon atoms, known as FT wax. The wax then goes through a process of catalytic cracking in order to produce drop-in hydrocarbons fuels including petrol, diesel and jet fuel, as well as LPG products propane and butane.

So long as the original feedstock material is derived from biomass, the FT-propane and FT-butane can be considered bio-based. However, if the FT plant uses refuse derived fuel (RDF) as a feedstock then the products will be partially renewable (around 50%), while in the case of using forestry residues as a feedstock, the output will be fully renewable.

Development status

Both gasification and Fisher-Tropsch synthesis are well-established commercial processes when using fossil feedstocks, such as coal and natural gas. However, when it comes to biomass, gasification to syngas is a complicated technology that few developers have fully commercialised. Most of the facilities convert syngas (derived from biomass) into heat and power, instead of converting it into advanced biofuels, due to the high syngas purity required to protect the catalyst in FT synthesis.

FT synthesis of syngas derived from biomass is maturing, but the attrition of catalysts, due to syngas impurities, can affect the ability of the process to operate reliably and to result in an acceptable and consistent end product. In addition, generally, gasification of MSW is not a proven technology. Gasification systems require high quality, homogeneous feedstock to operate reliably and efficiently. MSW are not a homogeneous feedstock and can result in syngas with many impurities which it can be challenging to clean and then convert into transport fuels through FT, because the catalysts can be deactivated. Thus, it is difficult to prejudge whether the integrated process, using biomass and/or MSW as feedstocks, will be proved after its commercial demonstration in a number of industrial sized facilities described below:

- **Velocys**, in collaboration with industrial partners Shell and British Airways, are planning to build two integrated FT gasification units in the UK and the USA, which will use MSW and woody biomass as feedstock, respectively. The current stage of development for the UK based biorefinery includes a detailed pre-FEED (Front End Engineering and Design) engineering study and site permitting activities. These activities are fully funded by the *Future Fuels for Flight and Freight* (F4C) grant and £4.5m committed by the project partners. Partial funding has also been secured for the completion of the whole project (a grant of £434k has been secured from the DfT under the F4C scheme) but at the moment, it is not clear whether the project will be commissioned, as it is subject to planning permission and funding. Similarly,

the USA based project has secured partial funding and is also subject to planning permission being granted. Velocys has proven their FT process in the ENVIA facility in Oklahoma City, producing renewable fuels from landfill gas. Therefore, they have not demonstrated their process using biomass or MSW as a feedstock, meaning that it is difficult to determine the likelihood of these facilities proceeding as planned.

- **Fulcrum** is currently building its first FT gasification facility (Sierra BioFuels Plant) in Storey County, Nevada. It is expected to become operational in 2020, processing approximately 175,000 tonnes of MSW annually, creating 47.73 million litres per year of renewable FT wax. However, it is not a standalone process and the FT wax will be transferred to an oil refinery for the production of drop-in fuels. Fulcrum validated the yield and the robustness of their process at demonstration scale in 2014, passing a stringent U.S Department of Agriculture 120-day continuous "MSW to fuel" test, meaning that there is the expectation that the Sierra BioFuels Plant will be operating reliably in 2020.

Joule & Red Rock and **KAIDI** are also planning to build industrial sized FT gasification facilities in USA and Finland, respectively. However, the development of these facilities is uncertain, as there has been no recent progress.

4.1.3 Methanol to Gasoline (MTG) gasification

Once syngas has been produced via gasification, another option for fuel production is via the production of methanol and subsequent methanol-to-gasoline synthesis. Drop-in liquid fuels are produced by reacting methanol over a bed of catalysts, producing significant quantities of LPG as co-products. This process is therefore a competing technology to the FT synthesis approach but the biopropane yields can be significantly higher, in the range 10-30%.

4.1.4 Dimethylether (Bio-DME) as an intermediate of the MTG process

The MTG gasification process described above involves the intermediate production of bio-dimethyl ether (bioDME) from methanol, which is then converted into gasoline. In particular, syngas is converted to methanol in the presence of a catalyst (usually copper-based), and then into DME by dehydrating the methanol in the presence of another type of catalyst (such as silica-alumina), prior to the production of gasoline.

DME can be blended with biopropane or used as an intermediate feedstock for the production of larger quantities of biopropane. A blend of up to 20% DME in LPG can be achieved without any changes to the supply infrastructure and boilers; for example, elastomers used in seals for conventional LPG are not compatible with higher DME blending levels. However, extensive testing must be performed to ensure the safety of any interventions and the compatibility with the existing infrastructure.

World production of DME currently stands at around 5-9 million tonnes per annum, primarily by means of methanol dehydration, but it is currently not available in European markets. It is mainly produced in China, Japan, Korea and Brazil, which have significant new production facilities, while new major capacity additions are planned or under construction in Egypt, India, Indonesia, Iran and Uzbekistan (IDA, 2019).

With regard to converting DME to LPG, the additional conversion cost has to be weighed against the benefits of producing LPG rather than simply blending DME into LPG. This process has not yet been

commercialised and there is no indication that progress has been made recently regarding the development of a new conversion facility. However, the University of Kitakyushu has developed a process using hydrogen, providing a pathway for LPG production if low-cost DME is available in specific locations, and the demand for LPG is relatively high. This technology uses hybrid catalysts consisting of zeolite and hydrogenation catalysts to convert DME (plus hydrogen) to LPG. The conversion of DME reaches nearly 100% with near-zero CO and CO₂ yields, but the technology has not yet been commercialised (Menecon, 2014).

4.1.5 Dehydration of Glycerol to Biopropane

Another pathway for the production of biopropane is via the dehydration of glycerol (aka glycerine). Glycerol is a major by-product from the production of soap and FAME biodiesel, with a mass yield of 10%. It has therefore attracted a considerable amount of interest as a low-cost feedstock within the bioeconomy.

Unlike several other available technologies, dehydration of glycerol results in bio-propane as the principal product. Glycerol has a similar chemical structure to propane, and thus the conversion yields can be very high in comparison to other processes. Two organisations, Biofuels Solutions and the Renewable Energy Group, are active in this area, although production is not yet commercialised.

4.1.6 Pyrolysis and Hydrogenation

Pyrolysis is similar to gasification in that it involves the rapid heating of biomass in an oxygen-starved atmosphere. However, the temperatures for pyrolysis are lower and the main output is liquid FPBO (fast pyrolysis bio-oil) as opposed to syngas. FPBO does have some potential to be used directly as a fuel, but its fuel properties limit the potential applications to boilers and heavy fuel burners. FPBO is acidic, contains particles of char and degrades during storage. Therefore, it must be upgraded via hydrotreating before it can be co-refined at existing refineries into a range of drop-in liquid fuels. Trace amounts of biopropane are present in off-gases of a pyrolysis plant but the majority of fuel produced via this route comes from the hydrotreating and co-refining stages.

Development Status

Pyrolysis of biomass is generally a well-proven technology, which can be used to produce fast pyrolysis bio-oil (FPBO). Some have demonstrated that FPBO can be burned in commercial scale boilers, but its fuel properties and storage limitations make it an unsuitable fuel for domestic heating without substantial further upgrading or hydrotreating. FPBO upgrading to produce drop-in transport fuels has not yet been proven and consequently, the overall process remains at a low TRL. However, improving FPBO properties through hydrotreating may also produce quantities of biopropane, as is the case with HVO production.

Biopropane is also produced during the pyrolysis process itself, from which it is likely to be recovered if present in significant quantities. The status of current and future developments is described below:

- **Ensyn** has already designed and commissioned a 3 million gallon per year fast pyrolysis plant in Canada (Odario). Although currently, pyrolysis oil is not upgraded at conventional oil refineries, and used for the generation of heat and power. In 2016, Ensyn announced that it had begun construction of a second pyrolysis facility in Quebec with local wood industry

partners. The plant will process 65,000 dry tonnes of forest residues per year producing 10 million gallons of pyrolysis oil. The plant was due to be operational by the end of 2018; however, there have been delays in the development phase and it has not yet been commissioned. Ensyn is also developing a 22 million gallon per year project in Brazil in a 50:50 JV with Fibria. The plant will be co-located at a pulp factory using eucalyptus residues with FPBO sent to heating clients and refineries in the US. While a detailed study is underway, basic engineering has been completed and the facility is at an early stage of development.

- **BTG-BTL** opened their first commercial scale fast pyrolysis plant in Netherlands in 2015, which produces 20 million litres of FPBO per year that is not upgraded but used for heat and power. In addition, BTG-BTL have signed a contract with Green Fuel Nordic for the construction of a new pyrolysis plant in Finland, which is expected to be operational by the end of 2020.
- **Setra** has announced the development of a fast pyrolysis plant in Sweden, which is expected to become operational in 2021 and create 25,000 tonnes of pyrolysis oil per year, if capacity is reached.
- **CRI/Shell** have commissioned a catalytic pyrolysis demonstration unit at the Shell Technology Centre in Bangalore, India⁹. This is a fully integrated process, where pyrolysis oil is upgraded for the production of drop-in hydrocarbons. Shell has the internal capabilities to upgrade the pyrolysis oil produced at their own refineries. The output capacity of the plant is not confirmed, although it appears to operate at 5 metric tonnes per day, using forestry residues.

4.1.7 Hydrothermal Liquefaction (HTL)

Hydrothermal liquefaction (HTL) has shown a lot of promise for the liquefaction of biomass at the research scale. Similar to pressure cooking, HTL uses water at high temperature and pressure to form an oil similar in appearance to FPBO derived from pyrolysis, which is known as bio-crude. Biocrude has some advantageous fuel properties over FPBO but it is still required to be hydrogenated and upgraded in order to be converted into drop-in fuels in existing refineries.

HTL also has the major advantage of being able to use feedstocks with a high moisture content, which may not be suitable for gasification or pyrolysis due to the high energy penalty of driving off the water contained in the feedstock. According to Atlantic Consulting, the refining of bio-crude in conventional oil refineries can lead to 4-5% yield of biopropane.

Development Status

In general, hydrothermal liquefaction (HTL) of lignocellulosic biomass appears to be at an early stage of development and is less mature compared to fast pyrolysis, which has been technically proven at several demonstration scale facilities. HTL has passed the proof of concept stage, but there are limitations that need to be overcome to be successfully validated at a larger scale, on a more continuous system. The main technical challenge is that during the reaction, the solubility of coke, tar, and solid residue in water is very low, and therefore, these substances form deposits, which may obstruct the equipment's functionality, affecting the robustness of the process.

⁹ The addition of a catalyst to the pyrolysis process results in the production of a higher quality pyrolysis oil, that can be more easily upgraded to drop-in fuels, which contain only molecules found in current hydrocarbon fuels.

Licella's demonstration plant (TRL 6-7) in Australia seems to be the largest operational facility worldwide and they claim that their process is controllable and delivers a consistent and high quality biocrude. However, the upgrading and refining of biocrude into drop-in fuels is unproven and needs further investigation. Although there is a good chance that the fully integrated process can result in biopropane, further investigation is required to determine whether the opportunities for producing biopropane are significant in terms of yields and robustness of the process.

To commercialise their process, Licella has set up a joint venture with Armstrong Chemicals to build an industrially sized plant in Teesside, in the North East of England. This facility appears to have secured funding and planning permission, and the developers report that construction will commence in 2019. When operational, the plant will convert end-of-life plastic waste that is unsuitable for mechanical recycling into adequate quality biocrude that can be mixed with conventional refinery feedstock¹⁰. If this HTL plant becomes a reality, sufficient quantities of biocrude will need to be tested at conventional oil refineries to evaluate opportunities of biocrude upgrading in drop-in fuels, including LPG. It should be noted however, that as the feedstock for this facility is fossil based - end of life plastics - it cannot result in any quantities of bio-based propane.

4.1.8 Aqueous phase reforming (APR)

APR is defined by the Royal Society of Chemistry as "*the reaction of biomass-derived oxygenated compounds [e.g. sugars, sugar alcohols and glycerol] in aqueous solution at low temperature in the presence of a platinum catalyst to produce hydrogen*".

Depending on the mode of the reactor and the choice of catalysts, the process can be optimised for the production of either hydrogen or hydrocarbons such as propane and butane (Murata et al., 2008). APR also has the advantage of operating at low temperatures and not requiring a drying stage, although some pre-treatment may be necessary to hydrolyse carbohydrates and release sugars.

Development status

At the moment, APR mainly utilises sugars from first generation biomass (such as corn and sugarcane), but the process can also use glycerol or lignocellulosic sugars, which would require significant pre-treatment and hydrolysis to achieve extraction of sugars (when using first generation feedstock the process is less complex). The use of lignocellulosic sugars has been performed only at laboratory scale where low yields of final products have been obtained due to the feedstock being less homogeneous, and impurities are introduced during the pre-treatment step.

Tesoro's demonstration plant in the USA is the world's largest facility, with capacity of 110 litres of biocrude, but it appears to be inactive at present, and there is no indication that the technology will be further developed in the near future. APR technology is generally less mature than pyrolysis and appears to be at the same TRL as hydrothermal liquefaction (TRL 6), although no progress has been made recently. However, the fully integrated process for the production of long chain hydrocarbons – through the upgrading the biocrude – is still unproven (low TRL), as only initial laboratory tests have been performed. Even though this does not directly affect the production of biopropane - which is

¹⁰ Licella plant description available at <https://www.licella.com.au/global-jv-armstrong-chemicals/>

produced during the APR stage – it will have an impact on the economics and commercialisation prospects of the process, as biocrude could be offered in lower value markets.

4.1.9 Fermentation of sugars to isobutene

Fermentation of sugars is another pathway that can lead to the production of bio-based isobutene (also known as bio-isobutylene). The most promising process through fermentation is IBN-One, developed by Global Bioenergies. This process converts sucrose into isobutene using genetically engineered microorganisms and appears to be proven at a demonstration facility in Germany, which is capable of producing 150 tonnes of final product per year. It should be noted that LPG mainly consists of propane and butane, but it can also include propene, butene and isobutene. In addition, Global Bioenergies have set up a joint venture with Crystal Union to build a commercial-scale facility in France, which is expected to become operational in 2022. The project is currently at the planning stage and is reported to produce up to 50,000 tonnes of isobutene per annum.

Even though isobutene can be mixed with conventional LPG, contributing to the decarbonisation of the UK heating sector, it is a major building block for the production of a wide range of chemicals, cosmetic ingredients, and fuels. These markets are expected to have an impact on the availability of isobutene for the decarbonisation of the heating sector, as Global Bioenergies have received 13 letters of intent, coming from the cosmetics, specialty fuels, road fuels and air transport industries, for purchases covering the capacity of the first industrially-sized isobutene facility¹¹. However, due to high demand for isobutene in the world markets, Global Bioenergies has the ambition to commission more commercial-scale plants in the future, which may increase availability of isobutene.

¹¹ <https://www.biofuelsdigest.com/bdigest/2018/12/02/global-bioenergies-gets-13-letters-of-intent-for-purchases-covering-the-capacity-of-its-first-plant-project/>

5 Feedstock Overview

The feedstocks used to produce biopropane have a major impact on the lifecycle greenhouse gas (GHG) emissions of the final product. In addition, feedstock availability constraints may be the most important factor in scaling up production to commercially competitive levels.

The feedstocks most likely to contribute in the commercial production of biopropane are bio-based oils (triglycerides), followed by woody biomass, MSW, glycerine and sugars. Table 4 presents a summary of the feedstock being processed, as reported by the developers. Although the technologies can potentially process multiple feedstocks, this does not mean that a facility can readily switch between different types. This is because processing will likely be optimised for specific types of feedstocks, e.g. sawmill residues, to retain product quality. Furthermore, feedstock supply will be contracted and so a steady, reliable stream of a given feedstock will likely be the case regardless of the technology.

Table 4. Summary of feedstock processing capabilities

Technology	Feedstock Capabilities
HVO	Bio-based oils (e.g. vegetable oils, used cooking oils (UCO), animal fats)
MTG gasification	Woody biomass, glycerine
Gasification and FT	Organic fraction of MSW, RDF, forestry residues, sawmill residues
Pyrolysis & Hydrogenation	Forestry residues, sawmill residues; BTG-BTL is also developing its technology to enable commercial production of crude pyrolysis oil from agricultural non-food residues.
Hydrothermal liquefaction (Cat-HTR™)	Mainly forestry residues but flexible to use any form of lignocellulosic biomass
Aqueous phase reforming (Virent's BioForming®)	Primarily sugars from first generation biomass but lignocellulosic feedstock can also be used as substrate
Dehydration	Glycerine
Fermentation to bio-based isobutene (Global Bioenergies)	Sucrose (from sugar cane and sugar beet) and possibly glucose (from corn and wheat); Global Bioenergies currently investigates the opportunities for producing isobutene from lignocellulosics

5.1 Feedstock requirements for active & planned developments

Hydrotreatment of triglycerides is currently the most promising route for the supply of biopropane in the UK. Even though the operational status of HVO facilities is not driven by the recovery of biopropane from the off-gas streams, evaluating bio-based oil requirements is critical, as the lack of their availability could restrict the opportunities for future recovery.

HVO plants, due to relatively high CAPEX costs, need to maximise their production capacity in order to be profitable. Assuming a very positive scenario where all the global installed capacity identified is utilised, around 4.3 million tonnes of bio-based oils are required (Table 6). However, based on the USDA report, only 54% of HVO capacity in Europe, which is by far the largest HVO producer worldwide, is forecast to be utilised in 2019, meaning that significantly lower volumes are used in real terms. Except for the HVO commercial plants, two industrially sized pyrolysis units, owned by Ensyn and BTG-BTL, have also been identified, that could potentially contribute to the production of biopropane with small quantities. These plants have an accumulated capacity of about 40,000 tonnes per year, which based on our estimation requires around 57,000 tonnes of woody biomass per annum.

Evaluating the feedstock requirements of planned developments is even more crucial as active plants already fully or partially reach their capacities. Table 7 summarises the feedstock requirements for planned facilities, assuming capacity limits are achieved. This analysis considers also gasification & FT, fermentation to bio-butene, and hydrothermal liquefaction technologies, for which there are currently no commercial plants. Glycerol dehydration and aqueous phase reforming technologies, analysed in chapter 4.1, are not included in the list because there is no indication that progress has been made recently regarding the development of an industrially sized facility.

5.2 Feedstock supply risks

Target feedstocks for these developments can be grouped into bio-based oils, woody biomass, MSW, RDF, and sugars. Demand for such feedstocks comes not only from these processes, but also other industries and a secure and stable supply is essential. An evaluation of availability is provided below.

Bio-based oils (triglycerides)

Sustainable sourcing of bio-based oils can be challenging, even for active HVO developments, and this could have an impact on biopropane production potential in the future. Bio-based oils can be virgin- or waste-derived, and include sunflower oil, rapeseed oil and used cooking oil (UCO), for example.

As measures against palm oil use in Europe are getting stronger¹², HVO producers using this feedstock must find ways to prove that their production is sustainable. Finding an alternative feedstock would be a significant challenge as palm oil is generally purchased at very low prices compared to soybean and rapeseed oils and can result in significant savings in HVO production costs.

In addition, due to their favourable sustainability credentials, there is a shortage of UCO and other waste-based feedstock in the global market, and availability in Europe will reduce further due to the increasing production of UCO methyl-ester (UCOME) in Asia. Combined with the expected increase in HVO capacity and the RTFO crop-cap, then European HVO plants may be struggling to secure sufficient quantities of suitable feedstock in the future.

Woody biomass

Fast pyrolysis, operating commercially by Ensyn and BTG-BTL, with other facilities planned, is designed to use woody biomass as a feedstock. Based on the estimates presented in Table 7, if all planned developments become operational, around 264,000 dry tonnes of woody biomass will be required to achieve capacity limits. This requirement can be considered feasible, given that global production of wood pellets exceeded 26 million tonnes in 2015, while in 2010 it was only 14.3 million tonnes (Thrän et al. 2017). However, feedstock supply risks are not completely mitigated, due to competing uses of woody biomass as a direct solid fuel in electricity generation and for residential heating.

It is important to note that these requirements refer to pyrolysis oil production for heat and power purposes (pyrolytic gases, that generally contain very small quantities of biopropane, are also produced). However, if the end goal is to upgrade the pyrolysis oil to drop-in fuels in conventional oil refineries and consequently increase the biopropane production potential, then the biomass

¹² EU will phase out palm oil by 2030 for its renewable energy targets. The phase-out doesn't mean a ban on palm oil in biofuels, as EU Member States will still be able to import and use palm oil-based biodiesel, but it will no longer be considered a renewable fuel or be eligible for the attendant subsidies.

conversion yields will be lower, and this would increase demand for forestry and sawmill residues further, to produce noteworthy quantities of drop-in fuels.

Gasification and FT synthesis is another process that can run on woody biomass. Currently, there are no commercial plants, but several industrially sized facilities are in planning, using woody biomass as feedstock. Gasification and FT appears to be more demanding in terms of feedstock volumes, compared to conventional fast pyrolysis (without considering pyrolysis oil upgrading), requiring up to 2.5 times more than pyrolysis plants of the same capacity. Therefore, sustainably sourcing adequate feedstock for all facilities identified in Table 7 could be an ongoing challenge.

Municipal solid waste and refused derived fuel

Currently, there are no operational facilities producing biopropane using Municipal Solid Waste (MSW) as a feedstock. However, the Velocys UK facility, which is in the planning stage, and Fulcrum's Sierra BioFuels Plant, that is currently under construction, can potentially produce some quantities of biopropane as a by-product, if become operational.

With regard to Velocys' facility, it is planned to use RDF as feedstock, which typically represents a mix of biogenic and plastic residual waste after metal and glass has been removed from the MSW stream. This means that not all of the diesel and propane produced from this facility could be claimed as bio-based. Feedstock availability is not expected to be a factor that would restrict the development of this plant, as approximately 2,900,000 tonnes of RDF were exported from the UK in 2018¹³, an amount equivalent to about 12 times the annual feedstock requirements of the Velocys plant. Significant quantities of RDF are currently exported because the UK has insufficient capacity for their treatment, and export remains a cheaper route of disposal than landfill. Therefore, RDF may be an underutilised resource in the UK and could be used to produce a range of bio-based fuels and products if incentivised.

When it comes to the Sierra BioFuels Plant, it is designed to extract recyclable materials from MSW and convert the remaining organic stream to drop-in transport fuels. Fulcrum has already secured large volumes of MSW through long-term agreements with a waste management company, to supply its under-construction facility in Nevada, and therefore risks associated with feedstock availability are minimal.

The facility announced by Licella and Armstrong Chemicals is not taken into consideration in this analysis, as the feedstock is fossil based - end of life plastics - and cannot result in any quantities of bio-based propane.

Sugars

The isobutene production facility announced by Global Bioenergies in France, which is due to be commissioned by 2022, is currently the only planned commercial scale plant that could use sugars as feedstock for the production of renewable LPG-like products. There are other technologies able to use sugar feedstocks, for example aqueous phase reforming and direct fermentation to biopropane, but these are not yet fully commercialised. The participation of Cristal Union, one of the largest sugar beet processors in Europe, in the joint venture with Global Bioenergies suggests feedstock supply is not expected to be a constraint. The facility will require 57,500 tonnes of sucrose to reach capacity, which

¹³ <https://www.letsrecycle.com/news/latest-news/rdf-exports-decline-in-2018/>

can be considered negligible in the context of the 2.2 million tonnes of sugars - in the form of crystallised, liquid or substrate sugar - sold by Cristal Union in 2017 (Cristal Union, 2018).

Another factor to consider is that after the abolition of sugar production quotas in 2017, table sugar prices are not deemed sustainable for beet and sugar production alone, as they have fallen below EU average production costs (CEFS, 2019). As a result, the European sugar sector has become more market-orientated, and EU white sugar prices have moved significantly closer to the world price, putting the sugar beet industry under significant pressure (Gaudoin, 2019). Therefore, the table sugar market is not expected to limit the availability of sucrose for isobutene production, as diversification of sugar beet outlets has become necessary.

6 Deployment Potential

There is significant potential for rapid scale-up of biopropane production and use, and the resultant impact could be significant in terms of benefits to the environment and the UK economy. There are a number of technical and commercial constraints that could delay or restrict availability, generally or more specifically to the UK market. Such constraints could be overcome through a combination of policy intervention and industry action. The potential impact, key challenges and potential actions are presented below.

6.1 Biopropane production opportunities

It is clear that biopropane co-produced from the **HVO process** is a promising opportunity for decarbonising the UK off-gas grid heating sector. NESTE's plant in Rotterdam appears to be the only HVO facility that currently recovers 40,000 tonnes of biopropane from off-gases, an amount equivalent to about 7.2% of the LPG demand in the UK residential and commercial heating sectors (550,000 tonnes in 2017 according to DUKES (2018)). For most of the remaining HVO developers, the extraction of biopropane from off-gases can be challenging but also technically feasible, and the reason for not upgrading their facilities is mainly market related, which can be overcome by giving the industry the right incentives and a stable offtake.

Assuming all global installed HVO capacity is utilised, then about 194,000 tonnes of biopropane can be extracted from the off-gases, which equates to 35% of the current LPG demand in the UK heating sector¹⁴. Approximately 100,000 tonnes of additional biopropane could become available, if all the planned developments become operational, at planned capacity. This 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. However, the supply of adequate sustainable bio-based oil is expected to be a challenge in future years, due to measures against palm oil use and competition for waste oils on the global market.

Fast pyrolysis is another technology that operates commercially and can lead to the production of biopropane, if C₃ and C₄ hydrocarbons are recovered from pyrolytic gases, which are currently used for their calorific value as process fuels. However, the quantities of biopropane and biobutane are not expected to be remarkable for their recovery to be considered as an option. However, notable quantities of biopropane can potentially be produced by upgrading (hydrotreating) pyrolysis oil in conventional oil refineries. Although this pathway is not currently commercialised, it has potential to diversify the mixture of feedstocks used for biopropane production.

Similar to fast pyrolysis, **aqueous phase reforming** and **hydrothermal liquefaction** result in a liquid phase product (biocrude) that can be upgraded, producing quantities of biopropane. Both processes are less mature than pyrolysis and the biocrude upgrading step is not expected to be proved in the short term, to allow the evaluation of the scale of opportunity. However, this is expected to change in the future due to limitations on crop-based feedstocks and growing support for development fuels. Hence this could be a promising pathway if APR and HTL continue to grow in TRL.

Gasification and FT synthesis is another route that can potentially result in biopropane as by-product. Currently, there are no commercial plants that can contribute towards this objective, but still,

¹⁴ Assuming 4.5% conversion efficiency of bio-oils to bio-propane.

several industrially sized facilities are expected to be operational in the future. Using Velocys' USA planned development - with an output capacity of 76,500 tonnes of FT liquids - as a reference point, and assuming that the yield of biopropane as a fraction of total output can be up to 7.5% by weight (Atlantic Consulting, 2018); to match LPG demand from the UK residential and commercial heating sectors would require the development of at least 87 plants, demanding around 30 million tonnes of woody biomass or RDF as feedstock. Although this presents a great challenge since there are so few GTL plants currently in operation, there is a great opportunity to produce a range of drop-in bio-based hydrocarbon fuels via this route. This has been recognised by E4Tech scenarios produced for the Department for Transport, which envision gasification and FT synthesis to be primary technology for the production of renewable transport fuels by 2040.

Fermentation of sugars to isobutene using genetically engineered microorganisms is a technology that is expected to be commercialised in the future, up to 50,000 tonnes per year by 2022, and this could also contribute to the production of biopropane. No data on technical challenges have been identified, but constraints appear to be more market related; isobutene is a major building block for the production of a wide range of chemicals, and there will be important competition on the market.

Methanol to Gasoline has been proven at demonstration scale using biomass as feedstock and is promising pathway for the production of biopropane. Although there is no indication that any significant progress has been made recently, the MTG process can result in significant quantities of biopropane compared to other technologies. Among the highest-yielding processes is the **Dehydration of glycerol** which results in biopropane as the main output. At the current time this is at low TRL but as the potential applications of biopropane become more apparent, the growing market demand may encourage suppliers to invest in this technology for its high yields and high GHG savings, particularly where the glycerol is sourced as a by-product of biodiesel production.

All the above technologies provide an opportunity for the UK to develop small scale and regional circular economies, helping the Government to achieve its targets and ambitions for greenhouse gas mitigation and growth of the indigenous bioeconomy. By investing in multiple technologies, developers can diversify the feedstock supply chain for their biopropane which minimises risk and prevents overexploitation of one feedstock or process.

6.2 Impact assessment

6.2.1 Heat

Of the existing properties that are off the gas grid, 193,000 British homes currently use LPG, and these could be easily transitioned to biopropane with no modifications required to the existing heating system. As such, this is likely to be the most cost-effective method of reducing greenhouse gas emissions from these properties. There are a further 200,000 homes using solid fuel but the most commonly used off-gas heating fuel is kerosene heating oil, used by 1.1m homes. As the Government plans to phase out fossil-fuel heating systems in new and existing properties through the 2020's, the potential for biopropane is expected to increase beyond the current housing-stock.

The emissions factors for different domestic heating fuels are given in Table 2. The air pollutant emissions of biopropane are expected to be identical to LPG, although lifecycle greenhouse gas emissions (in CO₂ equivalent) are reduced. The lifecycle CO₂e emissions and hence the potential

greenhouse gas savings of biopropane are highly dependent on the combination of feedstock and technology used. Currently, HVO is the only major commercially available source of biopropane but this process can utilise an assortment of feedstocks with varying upstream greenhouse gas emissions. At the present time, all biopropane available in the UK can be assumed to be derived from HVO with corresponding CO₂e emissions. In the future, however, biopropane is likely to be supplied from a variety of different processes each with its own unique sustainability criteria and therefore the fleet average CO₂e emissions for biopropane will differ from its current level.

Processes which use waste feedstocks and hydrogen derived from renewable resources have better sustainability credentials and lower emissions of CO₂e than processes which use crop-based feedstocks and hydrogen derived from steam methane reforming of natural gas. This is clearly shown in Figure 15.

It should be noted that most hydrogen currently used in HVO production is derived from fossil fuels and the values given in the figure assume no capture or utilisation of the CO₂ generated. Facilities such as the recently announced SkyNRG/KLM plant which use sustainable hydrogen produced from renewable resources (e.g. electrolysis of water using electricity produced from wind farms) may be capable of delivering CO₂e emissions savings approaching 90%. It is recommended that a full lifecycle analysis be conducted in order to properly assess the benefits of using sustainable hydrogen in HVO and biopropane production.

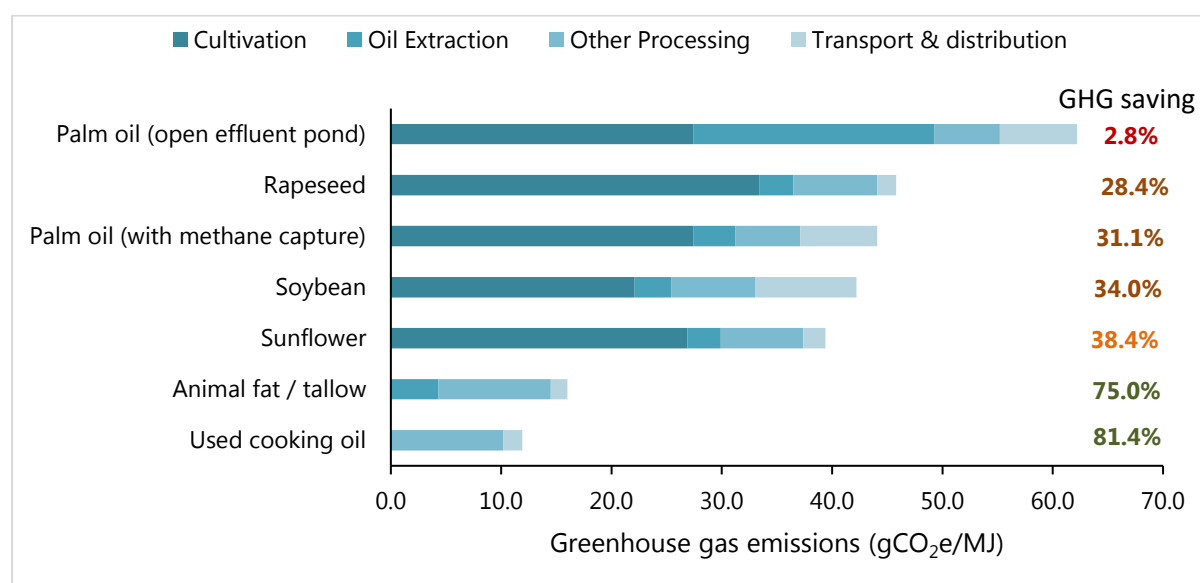


Figure 15. Typical disaggregated greenhouse gas emissions factors for HVO biopropane production according to Annex V of REDII¹⁵. The percentage emissions savings compared to fossil LPG are shown next to each bar.

Johnson (2017) reviewed the carbon footprint of biopropane generated from different HVO feedstocks with different use allocations. Assuming a 50% UCO and 50% rapeseed for energy allocation, this gives a mid-range value of 34.2 g CO₂e/MJ (123 g/kWh). This is a 49% saving compared to fossil propane, a 59% saving compared to heating oil and a 69% saving compared to

¹⁵ REDII refers to the recast Renewable Energy Directive (EU) 2018/2001. Emissions factors are stated for HVO production, but it is assumed that total emissions are allocated equally amongst the products on an energy basis.

coal. A summary of the emissions savings potential of biopropane compared to other off-grid heating fuels is given in Figure 16.

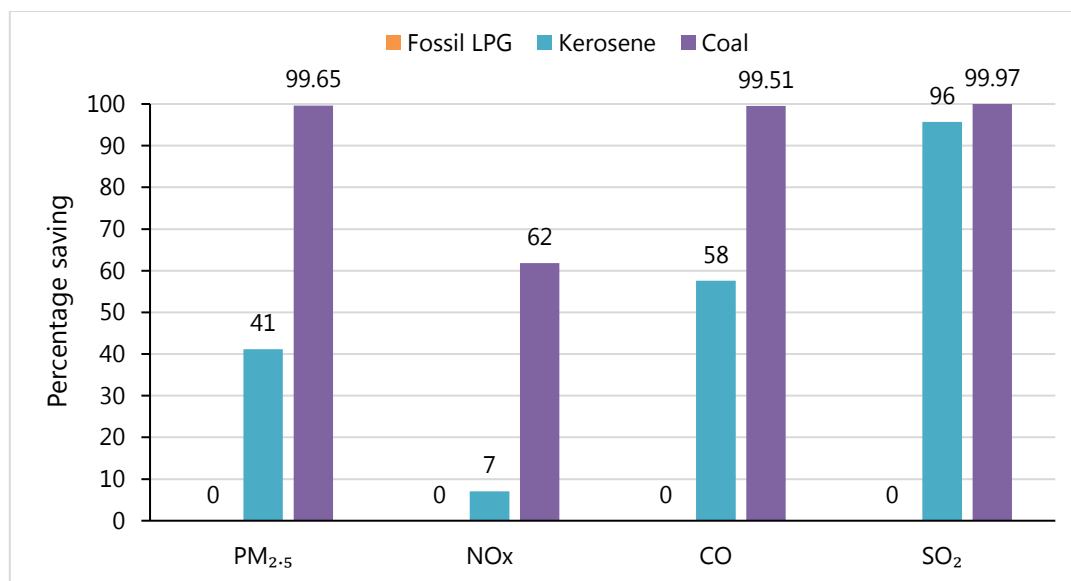


Figure 16. Potential emissions savings for domestic properties switching to biopropane

The greatest emissions savings can be achieved for properties currently using coal, although significant savings can also be made against kerosene heating oil. The 1.1m homes using heating oil could achieve emissions reductions of 59% in CO₂e, 41% in PM_{2.5} and 7% in NO_x by switching to biopropane (assuming the feedstock mix above). There may also be additional benefits through the transfer of tank ownership to the fuel supplier rather than the homeowner, as is the case for heating oil customers. Transferring existing LPG homes onto biopropane would require 199,240 tonnes of fuel, with an additional 15,680 tonnes in public buildings, 344,000 tonnes in commercial buildings and 85,000 tonnes in the agricultural sector. In total 643,650 of biopropane would be required to transition all users of LPG for heat. There is large potential for homes using heating oil to be converted to propane as these properties currently consume 1.9 million tonnes of kerosene per annum, equivalent to 1.8 million tonnes of biopropane.

6.2.2 Transport

The decarbonisation of road transport is expected to be led by electrification and there could be a major market for biopropane PHEVs or range extenders in the future. The versatility and low emissions factors of biopropane make it an attractive alternative to petrol in road vehicles, which can be converted relatively easily and can use the existing network of 1,200 filling stations.

HVO use in road vehicles can achieve modest reductions in NO_x (<10%) compared to fossil diesel, and 10-30% reduction in particulate matter (Neste, 2016). Conversely, LNG, CNG and LPG vehicles can achieve emissions reductions of more than 95% (see section 2.4 and electric vehicles are zero emission. This may affect biopropane availability as discussed in section 6.3 .

The 120,000-170,000 LPG vehicles would require 68,000 tonnes of biopropane if they were transitioned. In addition to heat, transport has experienced one of the slowest rates of

decarbonisation of all sectors. Converting vehicles to LPG and biopropane has the potential to rapidly reduce GHG emissions whilst also delivering cost savings on fuel, as described in section 2.4

6.3 Deployment pathway

Our analysis suggests that the total current biopropane production capacity is 183,000 tonnes, with a further 150 tonnes of bio-based isobutene. More than 99% of capacity is from HVO facilities, with other processes generally having a lower technology readiness level.

There are a further 11 plants currently under development which could add a further 100,000 tonnes of biopropane capacity before 2022, together with a further 50,000 tonnes of bio-based isobutene. HVO facilities also dominate the planned capacity, accounting for 94% of planned biopropane production capacity. A potential pathway to full conversion to biopropane in the UK by 2040 is shown in Figure 17.

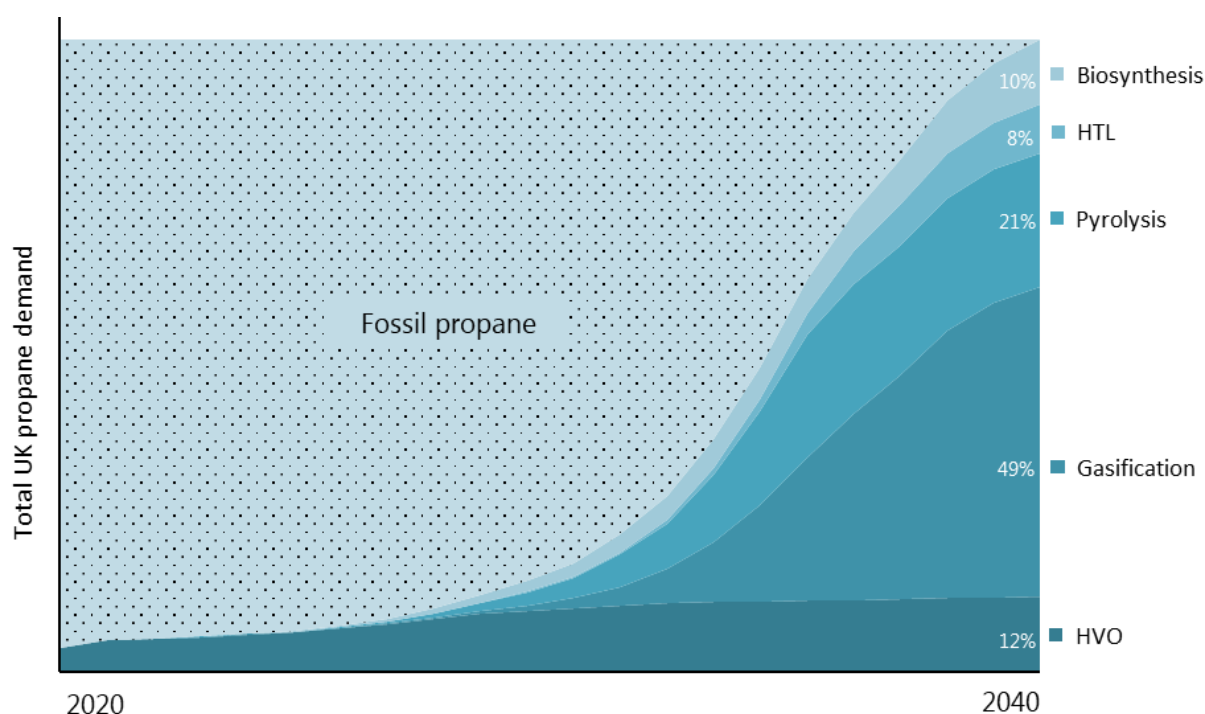


Figure 17. Potential route to achieve 100% biopropane by 2040

The potential route to achieving 100% biopropane supply by 2040 illustrated in Figure 17, includes contributions from a range of processes and technologies based on a realisable maximum scenario. The assumptions used here are consistent with work commissioned by the Department for Transport (E4Tech, 2017), examining the UK and global advanced biofuel production capacity to 2030.

HVO is expected to continue to be the predominant source of biopropane production throughout the 2020s and early 2030s. In this pathway, biopropane resulting from HVO production increases three-fold between 2019 and 2040. This is a conservative assumption based on limited availability of crop-based feedstocks, constrained by REDII and the RTFO. This trend and growth rate are consistent with evidence available on commissioning timelines for new plants and the scale-up of existing plants, which are listed in table 7 (see Appendix 4). In most cases, these plants are at a relatively advanced stage of development and are expected to reach maximum capacity before 2025; however, there may

still be further developments which have not yet been announced. In this potential pathway, the contribution of HVO drops below 50% of total production from 2030 onwards, due to other processes being developed in parallel.

It should be noted that in this pathway HVO refers only to hydrotreated vegetable oils and used cooking oils. Other processes such as HTL and pyrolysis produce intermediary products (biocrude and FPBO) which require further upgrading via hydrotreatment in order to produce drop-in fuels and biopropane as a co-product. Hence, hydrotreatment is required in both HTL and pyrolysis in this pathway, as well as in HVO production. This may be done in dedicated facilities but is likely to be more cost effective in existing refineries through co-processing. This also increases the diversity of feedstocks available to producers, adding flexibility to secure raw biological oils from a range of non-food crop feedstocks such as lignocellulosic biomass and wastes. Growing interest in waste feedstocks such as non-recyclable plastic, tyres and refuse-derived fuel may result in further bio- or partially renewable-propane production through pyrolysis and gasification routes.

Processes and technologies that are feedstock-flexible and produce a range of products, including drop-in fuels, are likely to deliver the greatest benefits for investors. Since propane is a by-product of many processes, procurement diversification is likely to minimise risk for suppliers. The complex array of biopropane formation pathways confounds the accuracy of future supply projections, and also stresses the need to match the most appropriate feedstock to a particular technology or process. For example, high moisture content feedstocks are likely to be more suitable for biosynthesis or HTL than for pyrolysis or gasification, which are more suited to dry lignocellulosic biomass. In addition, if future market demand for biopropane outpaces that of other biofuels then the technologies with the highest yield may be prioritised. Key examples include gasification and direct synthesis to biopropane, MTG gasification and the dehydration of glycerol. Since biopropane is the primary output of these processes, they may appeal less to an investor looking to spread risk but may be more relevant to suppliers looking to invest further in their supply chain. Investment costs of primary-output processes may be higher due to the reduced diversity of markets, but the high yields may increase profitability if biopropane experiences significant market growth through, for example, Government incentivisation.

Investments are already being made into novel processes, such as the production of sustainable aviation fuels from wastes in the UK; including waste plastics, aircraft tyres and municipal solid waste (by Advanced Plasma Power in Swindon and Velocys in Harwell). Demand for renewable jet fuel is growing and this is a major driver for innovation and commercialisation of processes which produce biopropane as a co-product. Most hydrogen currently used in HVO processing is sourced from natural gas via steam methane reforming and therefore the fuel is not fully renewable. Whilst there is a lot of potential for renewable hydrogen production through biomass gasification or water electrolysis, few plants are using renewable hydrogen at scale due to the high costs. However, this is beginning to change, for example the recent announcement on SkyNRG and KLM's new HVO facility that will use hydrogen produced from electrolysis and waste-derived feedstocks in its process.

In summary, HVO is likely to be the dominant process for biopropane production until 2030, with some growth in pyrolysis and co-processing during the mid-late 2020s. After 2030, gasification is likely to be the dominant process due to the wide range of feedstocks accepted and products generated. However, this potential pathway is highly sensitive to key factors, such as:

- Policy decisions (e.g. continuation of the RHI, transport decarbonisation, air quality legislation)

- Competitiveness of biopropane produced via different routes and whether different combinations of feedstocks and processes attract greater incentives.
- Transport policy pertaining to methanol fuel blends (up to a 20% blend in gasoline is advocated by some Governments but is not favoured in the UK. Therefore, more methanol may be available for the MTG gasification route.
- Support mechanisms for low carbon fossil fuels (e.g. hydrotreating of tyre pyrolysis oil)

6.4 Action Plan

In the absence of direct policy support for the production or use of biopropane in the UK, there is a significant risk that supply could be diverted elsewhere in Europe where more favourable market conditions prevail or, most likely retained in the country of production, where supply and distribution would be less complex and costly.

In order to make the UK attractive for producers, suppliers and investors in the biopropane supply chain, a number of critical policy interventions and industry actions may be necessary – these are summarised in Table 5 below.

Table 5: Actions required to increase UK biopropane supply and uptake

Development Opportunities	Action owner
Establish a UK supply chain for indigenous production of biopropane using British bioeconomy support and existing infrastructure (e.g. offshore wind for hydrogen for HVO production).	Government / Industry
Develop a roadmap for the UK market and communicate widely with producers.	Industry
Provide incentive for advanced fuel producers to capture biopropane, either in the form of investment support for additional capital or as long term, appropriately priced offtake agreements.	Government / Industry
Impose minimum GHG savings on biopropane as per REDII, encouraging producers to use the least intensive processes (e.g. renewable hydrogen and waste oil in HVO)	Industry
Provide incentive for consumers to switch to biopropane and provide protection for those in fuel poverty.	Government
Subsidise production for, and use in, the heat sector.	Government
Diversify procurement and supply chain by investing in novel processes and feedstocks, rather than relying on one specific technology.	Industry / Government
Conduct research into the best use of feedstock and highlight the benefits of HVO over FAME, e.g. drop-in nature and better cold weather properties.	Industry
Provide clear labelling on products so consumers understand the differences in fuel products and the risks associated with exceeding a 20% DME blend.	Industry

6.5 Investment Opportunities

There are many opportunities to invest in biopropane in the United Kingdom, both for industry and for national and devolved Governments. Biopropane is a very versatile low-carbon fuel with potential markets ranging from LPG vehicles to the petrochemical industry. It may also be used as a cooking fuel in caravans and boats or a heating fuel in off-gas grid homes and businesses. The latter is likely to be the dominant market due to the difficulties in decarbonising off-grid heating. Biopropane has a role in future scenarios put forward by the REA's Bioenergy Strategy, the CCC's Net Zero Technical Report and National Grid's Future Energy Scenarios.

Consequently, the biopropane market in the UK is likely to grow significantly to 2040 but currently suppliers are likely to be reliant on overseas facilities due a lack of indigenous production. Opportunities for investment include the development of new dedicated facilities such as HVO plants near the coast to utilise the UK's growing offshore wind resource. Other opportunities include investment in start-up companies and pilot plants for the commercialisation of the processes described in section 4.1 . Since biopropane is a by-product of several processes, investment in production facilities may yield multiple benefits including a diversified product range and additional revenue streams.

6.5.1 SWOT analysis for investors

Strengths	Weaknesses
<ul style="list-style-type: none"> • Versatile product with a variety of applications & diverse markets. • Low GHG emissions compared to fossil-equivalents in all sectors. • Substantially reduced PM and NOx emissions compared to solid and liquid fuels. • Able to be stored for long periods or injected into the grid. • Hydrotreating can be applied to a wide range of feedstocks to yield biopropane, other than crop vegetable oils including pyrolysis oil, algal oil and HTL bio-crude. 	<ul style="list-style-type: none"> • Versatility may lead to competing markets. • Only the HVO process has a high technology readiness level. • Currently reliant on imports. • Although low, lifecycle GHG emissions carry a high variability depending on the feedstock and process.
Opportunities	Threats
<ul style="list-style-type: none"> • Like-for-like fuel replacement in: <ul style="list-style-type: none"> ○ Domestic & commercial heating ○ Agricultural equipment and heating ○ Forklift trucks • Very rapid GHG reductions achievable at low cost for like-for-like replacements. • Biopropane can be blended with bio-DME or bio-based isobutene. • Potential to capitalise on growth in demand for HVO and other biofuels in aviation. • Biopropane is a by-product and so investment in facilities will yield multiple products. • Opportunity for carbon capture and storage with production. 	<ul style="list-style-type: none"> • Each sector is a potential competing market for a limited resource, which is likely to go to the highest value. • Limited amount of bio-based oil available for hydrotreating in HVO plants. • Increasingly limited amount of crop-based vegetable oils allowed in RTFO biofuels.

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Appendix 1: Technology Factsheets

Hydrotreated vegetable oil (HVO)

Hydrotreated vegetable oil (HVO), otherwise known as hydroprocessed esters and fatty acids (HEFA) or 'renewable diesel' is produced by the hydroprocessing of fatty acid feedstocks.

Hydroprocessing uses hydrogen to remove oxygen and produce saturated hydrocarbons which can be used as drop-in fuels in transport and other sectors. First oil must be extracted from the feedstock which might include milling and pressing of seeds and nuts, or the collection of used cooking oil, animal fats or oil from third generation biomass such as algae or non-food energy crops. The oils must go through a pre-treatment and purification stage to remove particles and impurities before being sent the hydroprocessing unit.

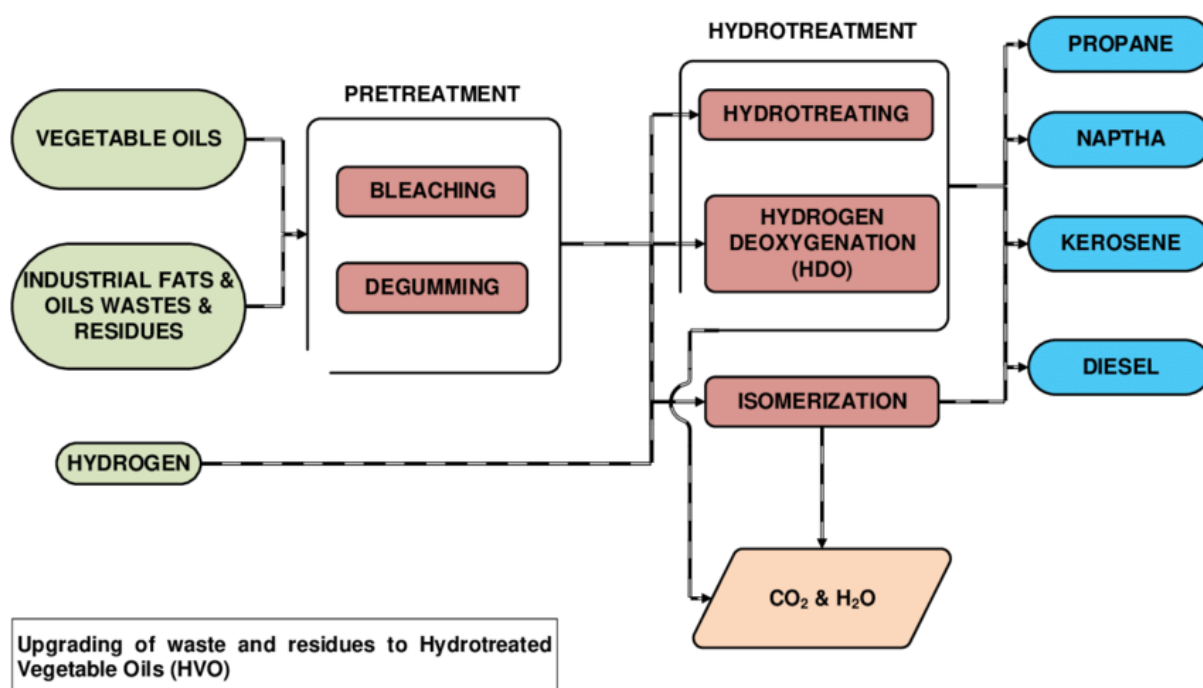


Figure 18. Simplified schematic of the hydrotreatment process. Source: Singh et al. (2018)

The transesterification process is a competing technology to HVO, using largely the same fat or oil feedstocks. Triglycerides are a type of lipid which is common in fats and oils. As shown in Figure 19, these compounds contain a propane/glycerol backbone attached to three chains of fatty acids via ester bonds. During hydrotreatment, hydrogen is used to cleave the propane backbone and fatty acid chains, with further hydrogen used to saturate the double bonds of lipid triglycerides. This typically takes place at elevated temperatures of 300-400°C and an overview of the chemical process is given in Figure 19.

During FAME biodiesel production, the glycerol produced is a waste product but in HVO production propane is formed instead which can be captured and marketed separately to the liquid fuel products. After hydrotreatment, the intermediate products undergo isomerization and hydrocracking to produce fuels which meet the specifications for use in road vehicles or in aviation.

Hydroprocessing is already performed at oil refineries to improve the properties of oil products derived from fossil fuels. Hydrogen is most commonly sourced from steam methane reforming of

natural gas but it can also be produced from gasification or from the electrolysis of water using renewable energy.

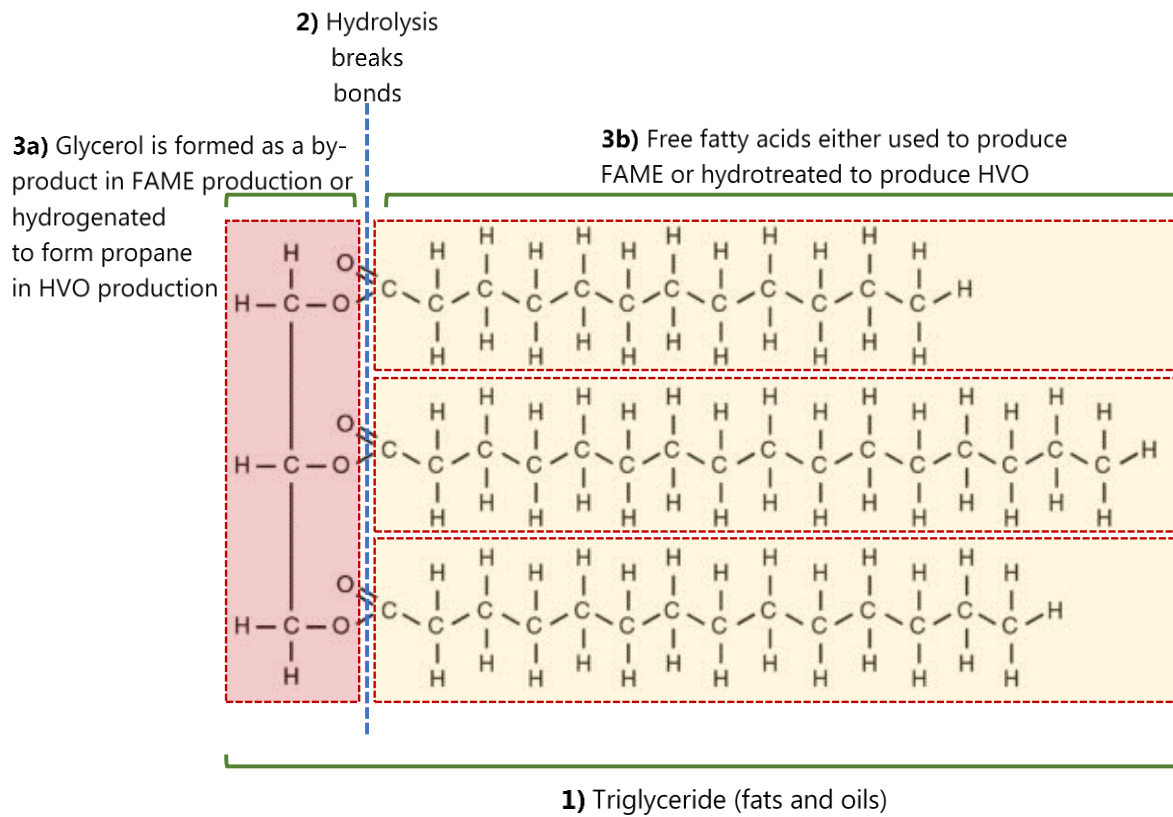


Figure 19. Chemical structure of bio-based oil and fat feedstocks.

Gasification and Fischer-Tropsch Synthesis

Another pathway that could potentially lead to biopropane as a by-product is the combination of gasification with Fischer-Tropsch synthesis. Gasification represents the conversion of carbonaceous material to gas (with small amounts of char formation). The process is typically conducted at temperatures between 800-900°C, and pressured using air, oxygen or steam as a gasifying agent to convert dried biomass to a low to medium energy gas known as syngas. Syngas is a mixture of mostly H₂ and CO and small amounts of CO₂, H₂O and CH₄. The exact composition of the gas varies depending on the composition of the feedstock but mostly on the gasification process conditions used.

Before the FT synthesis step, syngas is firstly 'cleaned-up' by removing impurities and tars, while the ratio of H₂ and CO is also altered. The FT synthesis then involves the 'condensation' of syngas into hydrocarbon alkanes using catalysts, which effectively act as 'anchors' upon which the carbon monoxide and hydrogen adsorb. Alkane chain growth begins once the carbon monoxide has been broken down, enabling the coupling of carbon and hydrogen and the separation of oxygen (which leaves as water molecules). Chain growth continues by adding further CO and H₂ until the newly formed hydrocarbon molecule is desorbed from the catalyst surface, a product known as FT wax.

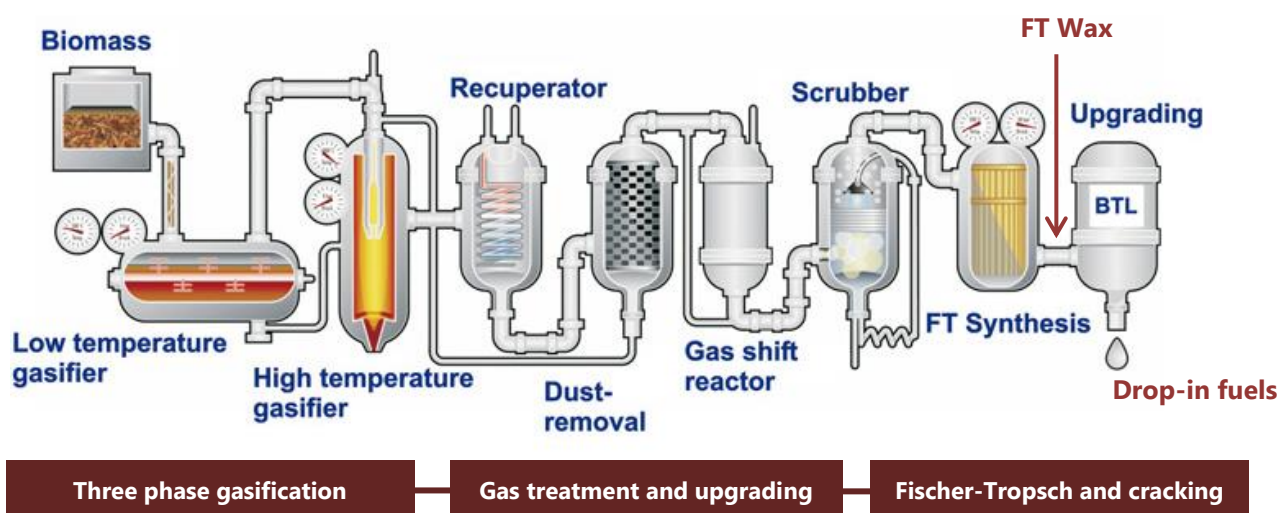


Figure 20. Gasification and Fischer-Tropsch process diagram. Source: Choren and ETIP Bioenergy¹⁶

FT wax is an intermediate product that consists of hydrocarbon compounds which have around 40 carbon atoms. However, the process targets drop-in fuels, and in particular diesel and/or aviation fuel, which have 12-18 carbon chain for diesel and 14-18 for aviation fuel.

To achieve diesel and jet fuel properties catalytic cracking of FT wax to smaller carbon atoms is required, meaning that there are shorter carbon chain molecules left (gasses) which can very likely be propane and butane, depending on targeted fuels and the carbon chain of the FT wax (number of C atoms). The process can be easily adjusted to produce different quantities of diesel and jet fuel, which may have an impact on the quantities of propane and butane produced; diesel is a straight-line carbon chain while in jet fuel there are some branches in the chain.

¹⁶ <http://www.etipbioenergy.eu/value-chains/products-end-use/products/ft-liquids>

As a side note, the catalyst during the synthesis or cracking process can be changed or modified to produce shorter carbon chains and increase the biopropane output. Nevertheless, larger carbon chains are more complicated - the lower the carbon chain the easier to make - and it appears that the production of renewable diesel and other mid-distillates benefits more the economics of the process.

Methanol to Gasoline (MTG) gasification

MTG gasification process is already at commercially ready level, but primarily with fossil feedstock including, natural gas or coal (after its gasification). Figure 21 presents the MTG process developed and marketed by ExxonMobil. ExxonMobil and Uhde demonstrated the process in a commercial scale facility in New Zealand, to exploit an offshore natural gas field. However, it should be noted that although the plant continues to produce methanol to date, gasoline production ceased in 1997 due to unfavourable economics. The fact that the plant does not produce gasoline anymore, means that the process cannot result in biopropane as a co-product.

More recently, a "2nd generation" MTG technology has been developed by ExxonMobil and demonstrated in China by Jincheng Antracite Mining Group (JAMG) in an industrially sized plant. The facility uses coal, rather than natural gas as a feedstock, and its output is 2,500 BPD gasoline per year. Exxonmobil's process appears to be proven at a commercial scale with stable production yields, product qualities and catalyst performance. However, it should be noted that the technology has not been proven using biomass as a feedstock; biomass gasification results in different syngas quality.

Regarding using biomass as a feedstock, MTG process is generally at a demonstration stage. Haldor Topsoe has developed TIGASTM, an MTG gasification process that runs on woody biomass as a feedstock (Figure 22).

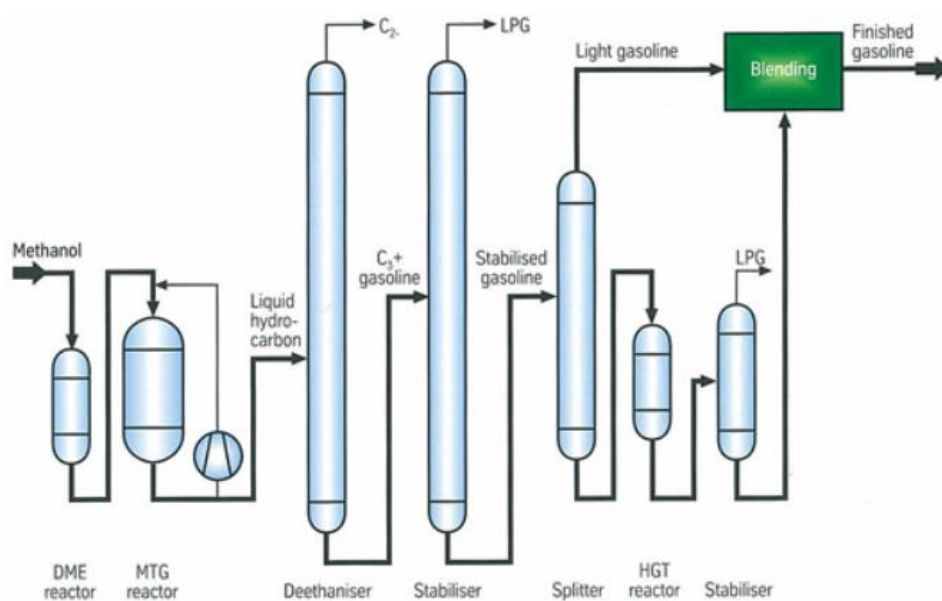


Figure 21. Methanol to gasoline process developed by ExxonMobil¹⁷

This process appears to be proven at a demo scale facility, between 2010 and 2014, as part of the 'Green Gasoline from Wood' project, funded mostly by the US Department of Energy; it should be noted that Haldor Topsoe has not built or owned a dedicated Demo facility and the demonstration took place probably in an open access facility. The demo plant was fed about 19 tonnes per day of wood and produced 23 barrels per day of gasoline and 3 barrels per day of LPG.

¹⁷ <https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/methanol-to-gasoline>

Finally, BIO-MCN modified an existing natural gas to methanol plant to run on glycerine, for the production of methanol, while there is an indication that the plant can be modified, with relatively ease, to produce Bio-LPG using glycerine as feedstock, a by-product from bio-diesel production. If this pathway proves to be feasible and the economics viable, then the availability of bio-LPG can be increased rapidly. However, at the moment, the facility simply turns biomethane into bio-methanol, using only a fraction of their capacity. Therefore, the status of the facility can be marked as idle.

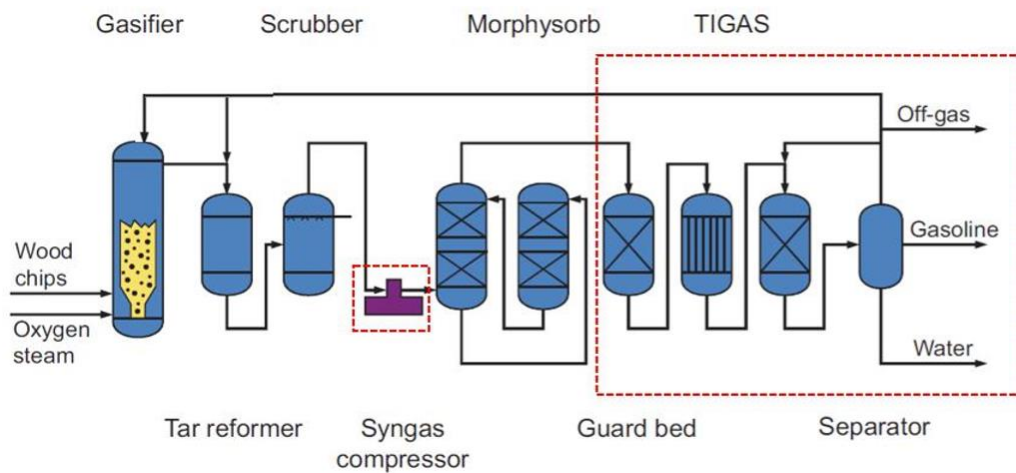


Figure 22. MTG gasification process (TIGAS™) developed by Haldor Topsoe¹⁸

¹⁸ https://brintbranchen.dk/wp-content/uploads/2017/10/Thoa-Thi-Minh-Nguyen_Topsoe.pdf

Dehydration of glycerol

Glycerol can be dehydrated to form acrolein and then hydrogenated to form propane, or directly converted into propane without the acrolein step.

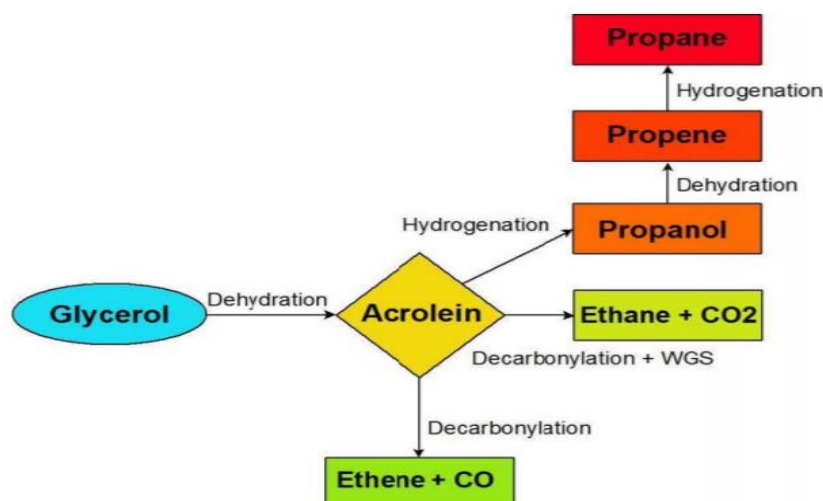


Figure 23. Biofuels Solutions technology; the reaction pathways from glycerine to bio-propane¹⁹

BioFuels Solutions has developed a glycerine dehydration technology, that appears to be proven in laboratory scale. More specifically, their process involves the dehydration of glycerine to produce acrolein and then hydrogenating it to produce propanol and finally propane through further processing (Figure 23). BioFuels Solutions appears to seek funding for building a pilot plant for demonstrating their technology, but to the best of our knowledge, this has not been achieved yet. Alternatively, acrolein may be converted to ethylene or ethane by decarboxylation (Figure 23).

Another technology has been developed by Renewable Energy Group, which seems to be considering the direct conversion of glycerol to bio-propane, without the intermediate production of acrolein. Both technologies are at low technology readiness level and there is no indication that they will be scaled up soon.

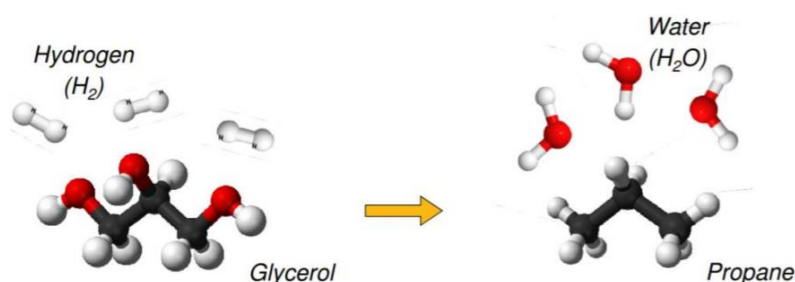


Figure 24. Renewable Energy Groups' glycerine to bio-propane process²⁰

¹⁹ <http://sgc.camero.se/ckfinder/userfiles/files/SGC198.pdf>

²⁰ <https://www.wlpga.org/wp-content/uploads/2018/10/BioLPG-The-Renewable-Future-2018.pdf>

Pyrolysis and hydrogenation

The pyrolysis process involves the thermal decomposition of biomass in the absence of oxygen, and can potentially result in the production of Biopropane. Depending on the pyrolysis process' heating rates, final temperatures, residence time and biomass particle size, the pyrolysis process will yield different proportions of solid, liquid and gaseous products.

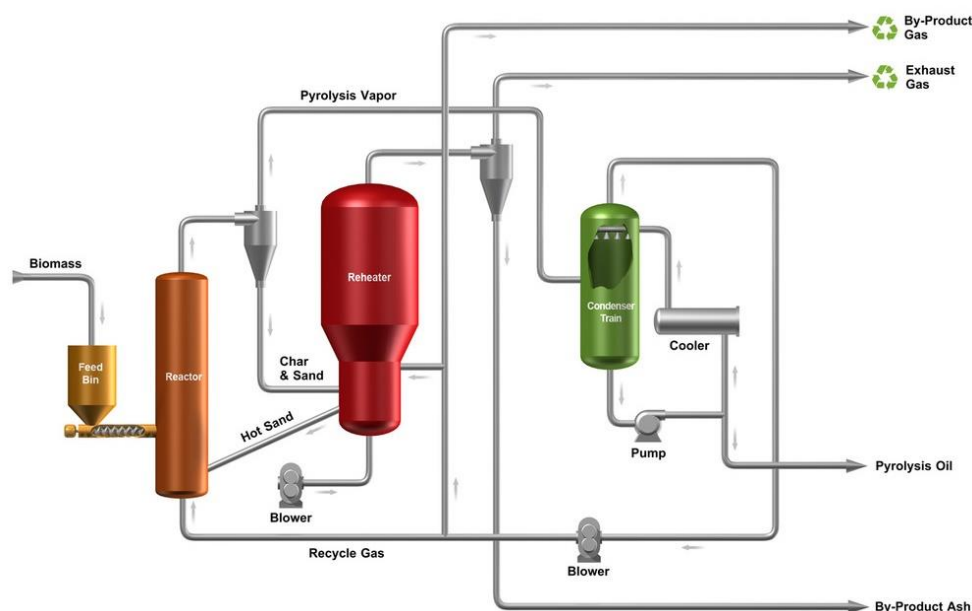


Figure 25. Simplified fast pyrolysis process developed by Ensyn²¹

Slow pyrolysis targets solid charcoal as a main product, while fast pyrolysis favours the formation of liquid products ('fast pyrolysis bio-oil or FPBO') and uses fast heating rates using temperatures of ~450-550°C with short final residence times (~1 second). These processing conditions enable biomass to decompose rapidly producing mostly vapours and radicals that are then quickly cooled and condensed into FPBO; some char and gases are permanent and are considered as by-products (figure 3); the 'faster' the pyrolysis process the higher the gas content, meaning that if the pyrolysis is slow then the product is mostly biochar so the opportunities for LPG production are limited.

The pyrolytic gases come as a mixture of methane, ethane, propane, butane, meaning that the latest two can be separated from the gaseous stream and potentially meet LPG heating fuel specifications. For example, the literature data show that the main components of pyrolytic gas from tyres are carbon monoxide, carbon dioxide, hydrogen sulphide, and light hydrocarbons like methane, ethane, ethene, propane, propene, butane, butene and butadiene, while their calorific value is about 30-50 MJ/m³²². However, a related point to consider is that pyrolytic gases are typically used as a process fuel

Additional LPG can potentially be produced, if there is an upgrade of the pyrolysis oil in an oil refinery and mixed with fossil oil. This pathway will mainly result in mid distillates but according to Atlantic consulting report, Biopropane can also be produced (1-2% of the final output). As a side note, the feedstock used in the pyrolysis process needs to be based on biomass for the LPG output to be considered as bio-based.

²¹ <http://www.ensyn.com/overview.html>

²² <https://www.degruyter.com/downloadpdf/j/eces.2012.19.issue-3/v10216-011-0035-6/v10216-011-0035-6.pdf>

Hydrothermal liquefaction (HTL)

Contrary to pyrolysis, the Hydrothermal Liquefaction (HTL) process uses water at relatively high temperature (200-400 °C) and pressure to form a dark, viscous, odorous bioliquid known as biocrude as well as a gas fraction and a solid residue, which are considered as by-products (Figure 26).

Oil derived from hydrothermal liquefaction is significantly different compared to pyrolysis oil. It has higher calorific value, lower oxygen content and greater stability. Therefore, biocrude is expected to require less extensive upgrading than pyrolysis oils and theoretically it is suitable to be blended with traditional fossil crude and dropped into existing refineries to make the same range of fuels, which can potentially include the production of LPG. According to Atlantic consulting, the refining of biocrude in conventional oil refineries can lead to 4-5% Bio-LPG.

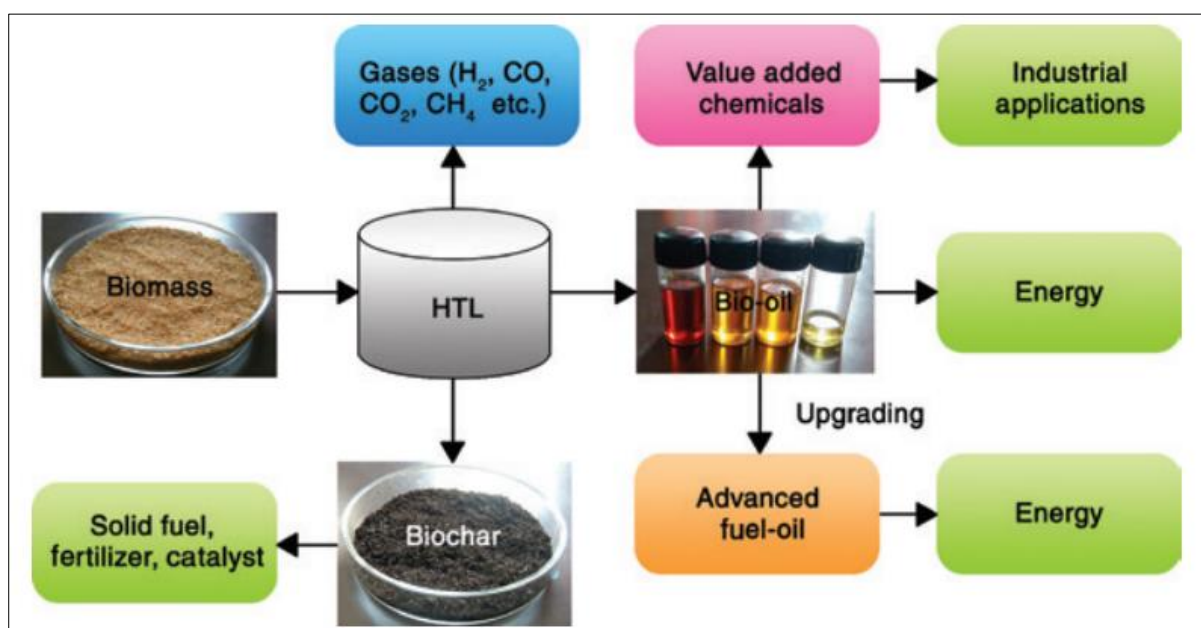


Figure 26. Product distribution of HTL and its possible applications.

Relatively small quantities of propane or butane can also be formed as part of the gas fraction during the HTL process. However, to the best of our understanding their concentration in the gas stream is generally lower compared to molecules that composed of less carbon atoms, such as methane and ethane.

Aqueous phase reforming (APR)

In aqueous phase reforming (APR), an aqueous solution of sugars is converted by a high temperature reforming process using a chemical catalyst to produce biocrude, a mixture of acids, ketones, aromatics and cyclic hydrocarbons, plus hydrogen and water. Further processing steps are then required to produce gasoline, diesel and jet fuel; this requires a series of condensation reactions to lengthen the carbon chains in bio-crude, before hydrotreating and isomerisation²³.

The Aqueous Phase Reforming process was initially developed (at the University of Wisconsin-Madison) to produce biopropane as a main product. However, the process was modified by Virent (acquired by Tesoro), to primarily produce longer chain hydrocarbons (gasoline and diesel), as these products are expected to be more in demand, improving the economics of the technology (Figure 27).

It should be noted that this process has low selectivity to liquid long-chain hydrocarbons and current production results in a large number of by-products including a gaseous stream, which contains a mixture of C1 to C4 alkanes. The actual Biopropane yield (C3 and C4 hydrocarbons) is currently not available, but it is expected that if the process is successfully commercialised, it will be used as a process fuel. Theoretically, LPG can be recovered from the gaseous stream and marketed separately but in that case, it must be replaced with another energy carrier, such as lignin, if the process involves the pre-treatment of lignocellulosic materials, for example ²⁴.

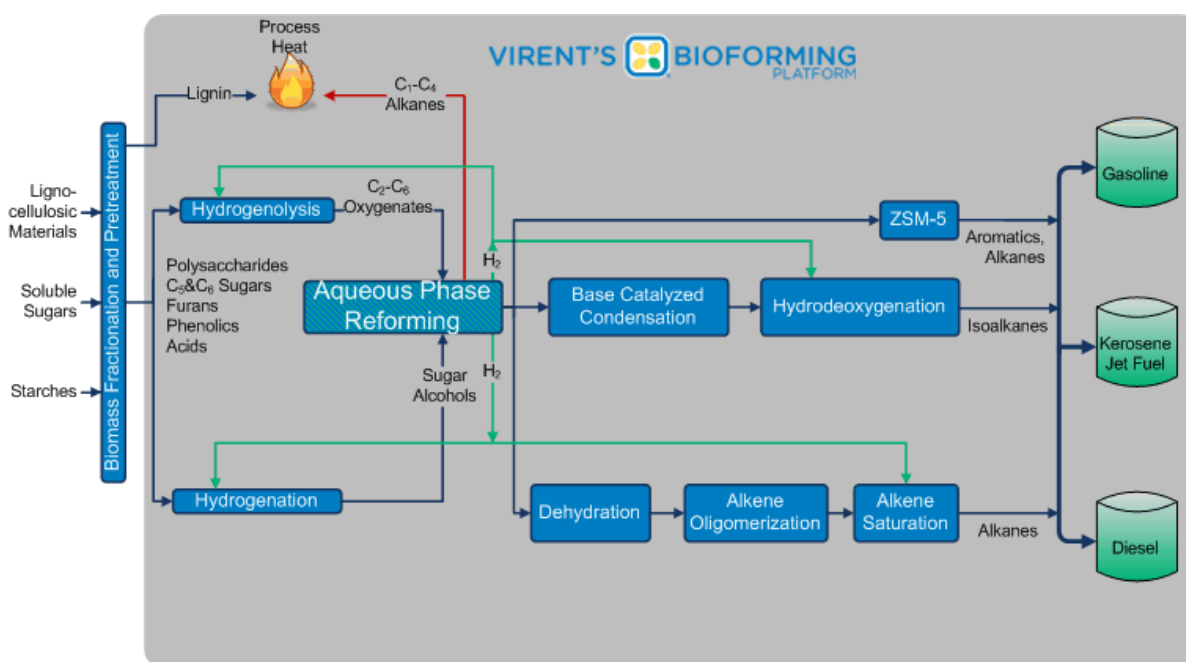


Figure 27. Process diagram for aqueous phase reforming²⁵

²³ https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/652538/advanced-drop-in-biofuels-uk-production-capacity-outlook-2030.pdf

²⁴ https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/376487/RHI_Evidence_Report_-_Biopropane_for_Grid_Injection_2_2_.pdf

²⁵ <https://newenergyandfuel.com/http://newenergyandfuel.com/2008/09/24/the-new-gasoline/virents-bioforming-platform/>

Appendix 2: Map of UK Oil Terminals



Figure 28. Map of UK oil terminals. Source: <https://www.oilterminalmap.co.uk/map/>

Appendix 3: List of Active Production Facilities

Table 6. Estimated feedstock requirements for operational HVO and pyrolysis facilities to achieve capacity limits²⁶

Company	Technology	Plant capacity	Feedstock type	Feedstock requirements (tonnes per year)	Comments
NESTE oil (Netherlands)	HVO	1,000,000 tonnes	Bio-based oils (including vegetable oil, animal fat, and UCO)	1,124,000	Feedstock requirements have been calculated assuming a typical 89% bio-based oil conversion efficiency to diesel.
NESTE oil (Finland)	HVO	260,000 tonnes	Bio-based oils (including vegetable oil, animal fat, and UCO)	292,000	Feedstock requirements have been calculated assuming a typical 89% bio-based oil conversion efficiency to diesel.
NESTE oil (Finland)	HVO	260,000 tonnes	Bio-based oils (including vegetable oil, animal fat, and UCO)	292,000	Feedstock requirements have been calculated assuming a typical 89% bio-based oil conversion efficiency to diesel.
NESTE oil (Singapore)	HVO	1,000,000 tonnes	Bio-based oils (including vegetable oil, animal fat, and UCO)	1,124,000	Feedstock requirements have been calculated assuming a typical 89% bio-based oil conversion efficiency to diesel.
ENI (Venice)	HVO	580,000 tonnes	Bio-based oils (mainly palm oil)	652,000	Feedstock requirements have been calculated assuming a typical 89% bio-based oil conversion efficiency to diesel.
World Energy (USA)	HVO	125,000 tonnes	Bio-based oils (mainly tallow)	140,000	Feedstock requirements have been calculated assuming a typical 89% bio-based oil conversion efficiency to diesel.
Renewable Energy Group (USA)	HVO	250,000 tonnes	Bio-based oils (not specified but triglycerides)	281,000	Feedstock requirements have been calculated assuming a typical 89% bio-based oil conversion efficiency to diesel.
Petrobras (Brazil)²⁷	HVO	230,000 tonnes	Bio-based oils (not specified but triglycerides)	258,000	Feedstock requirements have been calculated assuming a typical 89% bio-based oil conversion efficiency to diesel.
Sinopec (China)	HVO	20,000 tonnes	Bio-based oils (not specified but triglycerides)	22,000	Feedstock requirements have been calculated assuming a typical 89% bio-based oil conversion efficiency to diesel.
Sunpine (Pitea)	HVO	100,000 tonnes of HVO diesel	Bio-based oils (not specified but triglycerides)	112,000	Feedstock requirements have been calculated assuming a typical 89% bio-based oil conversion efficiency to diesel.

²⁶ This analysis does not include refineries that co-process petroleum streams together with bio-oils and biorefineries that use mainly tall oil as feedstock; tall oil, contains free fatty acids, and it is not a suitable feedstock for the production of biopropane, due to the absence of glycerol molecule.

²⁷ Petrobras announced they will terminate their biofuel production activities.

Ensyn (Canada)	Fast pyrolysis	13,600 tonnes	Forestry residues	18,000 – 19,500	Based on the biomass (expressed in dry tonnes) to pyrolysis oil conversion yield reported by the developer (70 to 75%).
BTG-BTL (Netherlands)	Fast pyrolysis	24,000 – 30,000 tonnes	Clean wood residues	34,000- 43,000	Feedstock requirements have been calculated based on biomass to pyrolysis oil conversion yield reported by the developer (70%), assuming yield refers to dry biomass.

Appendix 4: List of Planned Production Facilities

Table 7. Estimated feedstock requirements for planned industrially sized developments to achieve capacity limits

Company	Technology	Plant capacity	Feedstock type	Feedstock requirements (tonnes per year)	Comments
ENI (Sicily, Italy)	HVO	600,000 tonnes HVO diesel	Bio-based oils (including vegetable oil, animal fat, and UCO)	ca. 675,000	Feedstock requirements have been calculated assuming 89% bio-based oil conversion efficiency to diesel.
Emerald Biofuels (USA)	HVO	280,000 tonnes HVO diesel	Bio-based oils (non-edible oils and fats)	ca. 315,000	Feedstock requirements have been calculated assuming 89% bio-based oil conversion efficiency to diesel.
Petrexo (UAE)	HVO	400,000 tonnes HVO diesel	Bio-based oils (not specified)	ca. 449,000	Feedstock requirements have been calculated assuming 89% bio-based oil conversion efficiency to diesel.
ST1 (Gothenburg)	HVO	100,000 tonnes HVO diesel	Bio-based oils (not specified)	ca. 112,000	Feedstock requirements have been calculated assuming 89% bio-based oil conversion efficiency to diesel.
Total (France)	HVO	500,000 tonnes HVO diesel	Bio-based oils (60-75% vegetable oils (mainly palm oil), and 25-40% UCO and animal fats)	ca. 652,000	Feedstock requirements have been calculated assuming 89% bio-based oil conversion efficiency to diesel.
BTG-BTL/Green Fuel Nordic (Finland)	Fast pyrolysis	24,000 tonnes per year of pyrolysis oil	Mainly sawmill residues	ca. 34,000 (dry)	Feedstock requirements have been calculated based on the biomass to pyrolysis oil conversion yield reported by the developer (70%), assuming yield refers to dry biomass.
Setra (Sweden)	Fast pyrolysis	25,000 tonnes per year of pyrolysis oil	Sawmill residues	33,000-36,000 (dry)	Setra reports 85,000 tonnes per year of woody biomass will be used to reach capacity (assumed fresh weight). A corrected value is stated using standard yield estimate.
Ensyn and Fibria	Fast pyrolysis	98,000 tonnes per year of pyrolysis oil	Eucalyptus residues from paper mill supplemented by material from local, managed plantations.	130,000 to 140,000 (dry)	Based on the biomass (expressed in dry tonnes) to pyrolysis oil conversion yield reported by the developer (70 to 75%).
Ensyn, Arbec Forest Products and Groupe Rémahec	Fast pyrolysis	48,000 tonnes per year of pyrolysis oil	Mainly sawmill residues	ca.65,000 (dry)	Feedstock requirements have been reported by the developer.

Global Bioenergies & Cristal Union (France)	Fermentation	50,000 tonnes per year of isobutene	Sucrose (from sugar cane and sugar beet) and possibly glucose (from corn and wheat)	ca. 57,500	Based on the sugar to isobutene conversion yield reported by Global Bioenergies (87%).
Licella & Armstrong Chemicals	hydrothermal liquefaction (Cat-HTR™)	Not available	End of life plastics that are currently disposed to landfill.	20,000	Feedstock requirements have been reported by the developer. *Fossil-based Plastic cannot result in Biopropane.
Velocys (USA)	Gasification & FT	Around 76,500 tonnes of diesel and jet fuel	Forestry residues (woody biomass removed from forests to reduce the risk of wildfires).	306,000 - 383,000 (dry)	Assuming a typical yield of 20-25%, for the conversion of dry biomass to diesel.
Velocys, Shell, and British Airways	Gasification & FT	Around 53,100 tonnes of diesel/jet fuel	Post-recycled waste (RDF) otherwise destined for recycling or incineration.	ca. 212,000 - 266,000	Assuming a typical yield of 20-25%, for the conversion of dry biomass to diesel.
Joule & Redrock	Gasification & FT	Around 60,000 tonnes of diesel	Forestry residues	136,000	Feedstock requirements reported by the developer; unclear whether based on wet- or dry-basis.
Fulcrum	Gasification & FT	47.73 million litres Syncrude	MSW	175,000	Feedstock requirements reported by the developer.
KAIDI	Gasification & FT	Around 150,000 tonnes of diesel	Forestry residues and sawmill by-products.	600,000-750,000 (dry)	Assuming a typical yield of 20-25%, for the conversion of dry biomass to diesel.

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



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