The Bioeconomy Consultants NNFCC

A business case for an indigenous BioLPG supply chain in the UK

Prepared for Liquid Gas UK

September 2020

Release Date:	September 2020	
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Disclaimer

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

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Glossary of key terms

Term	Description
ATC	Advanced Thermochemical Conversion
CAPEX	Capital expenditure
CCC	Committee on Climate Change
CI	Carbon Intensity
DME	Dimethyl Ether
EfW	Energy from Waste
EIF	Energy Investment Fund
FEED	Feasibility and Front-End Engineering and Design
GHG	Greenhouse gas
HVO	Hydrotreated Vegetable Oil
LEPs	Local Enterprise Partnerships
LPG	Liquified Petroleum Gas
MSW	Municipal Solid Waste
NOx	Nitrogen oxides
PM	Particulate matter
RDF	Refuse Derived Fuel
RHI	Renewable Heat Incentive
RTFCs	Renewable Transport Fuel Certificates
RTFO	Renewable Transport Fuel Obligation
SMEs	Small and Medium-sized Enterprises
SNG	Synthetic Natural Gas
UCO	Used Cooking Oil

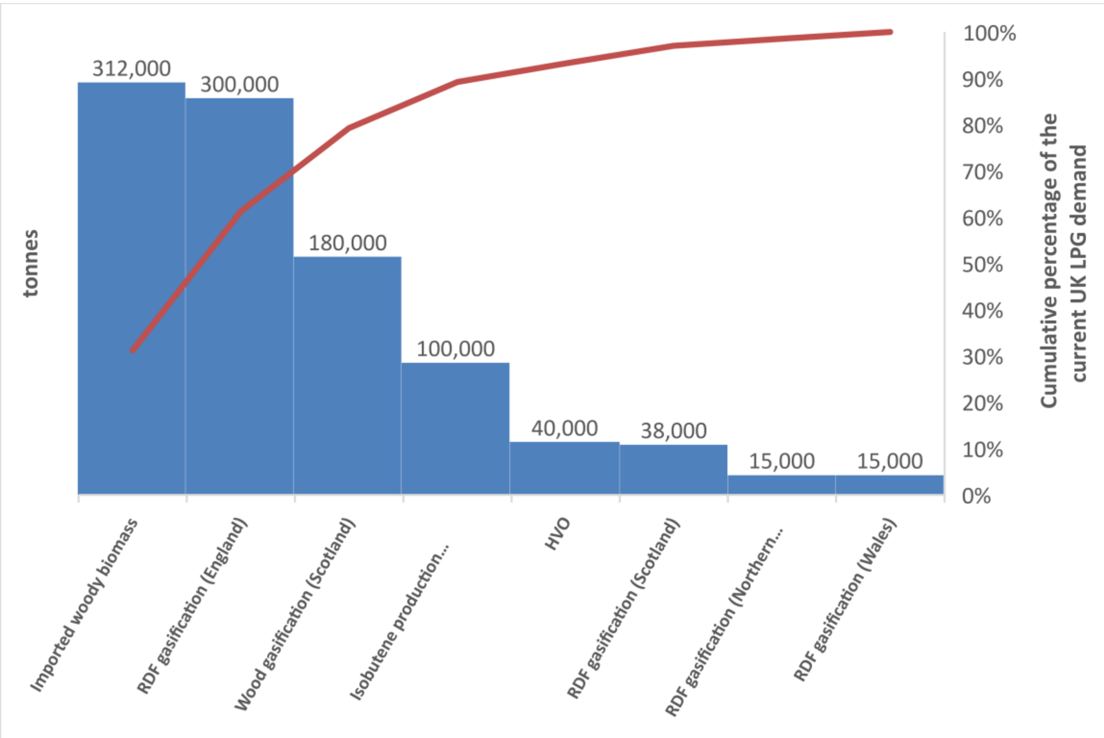
Executive Summary

Although electrification is expected to be the most widely adopted solution for the UK government to meet its net zero target, even in the most ambitious decarbonisation scenarios, there is still a residual gas demand which allows a significant role for green gases, mainly in the provision of heat in hard-to-decarbonise sectors. Bio-LPG has a key role to play, particularly, for rural sites that are off-the gas grid, where electricity grid capacity is limited and the use of high carbon emission fossil fuels for space and water heating is far more common. This is due to its following characteristics:

1. BioLPG is chemically identical to fossil LPG, being 100% compatible with existing supply networks and end-use infrastructure.
2. In comparison to biomethane and hydrogen, BioLPG liquefies at a lower pressure at room temperature, which allows its cost-effective distribution and storage in off-gas applications.
3. BioLPG results in substantially reduced carbon, PM, and NOx emissions compared to solid and liquid fossil fuels.

A previous study conducted on behalf of Liquid Gas UK revealed that a deployment pathway for a full switch from fossil to BioLPG in the UK by 2040 is feasible. However, at the current time, LPG suppliers are reliant on overseas facilities due a lack of indigenous production, and as a result there is significant competition from markets in other countries, which already have a high demand for LPG for heating, cooking, or transport.

There is significant potential for investment in indigenous production facilities in the UK, using British bioeconomy support and existing infrastructure. Domestic production will lead to the creation of green jobs, as well as in secured supplies that will support the UK to meet its decarbonisation targets. A potential production route for the development of an indigenous supply chain is illustrated below.

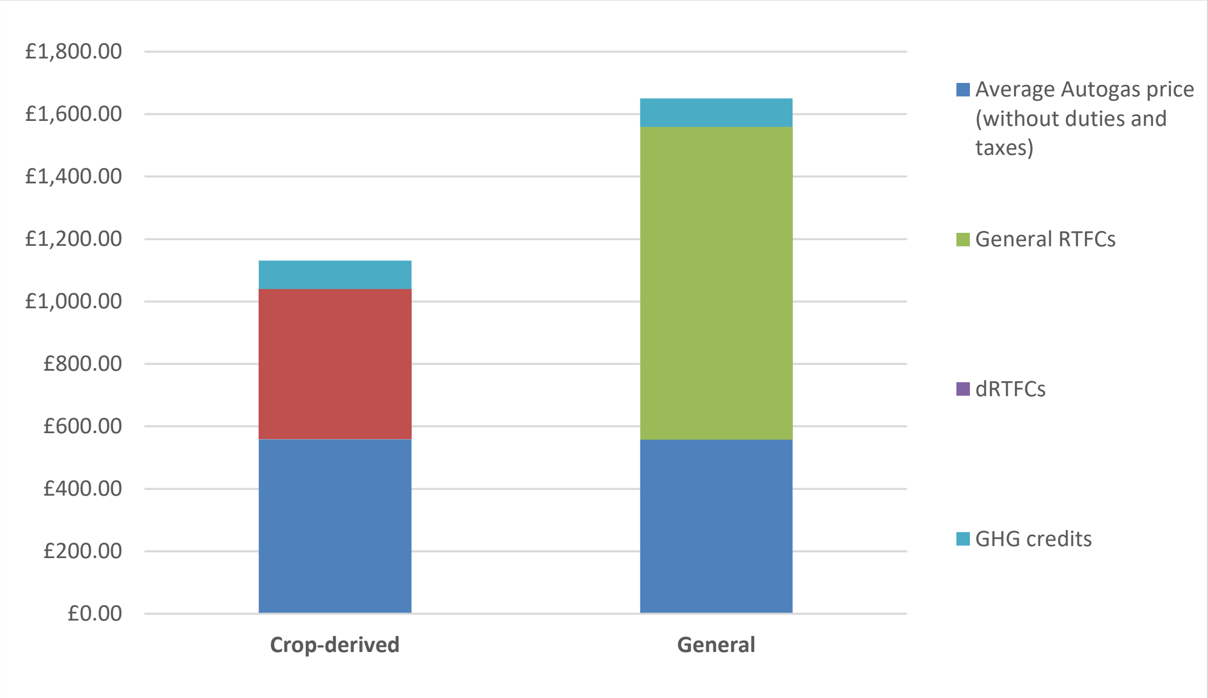


The only process to produce BioLPG that is currently operating at the commercial scale is the hydrogenation of vegetable oils, fats, and biomass-derived oils. Large volumes of bio-oils can be co-processed with petroleum intermediates to produce HVO diesel and BioLPG as a by-product, in existing UK oil refineries, at almost no additional capital cost.

Gasification is expected to be the dominant production technology, utilising a range of domestically available feedstocks including sustainable woody biomass and RDF, while importing sustainable woody biomass can boost production. Still, this potential cannot be realised in the short term, as gasification-based pathways for the production of BioLPG, as a main product, appear to be at an early stage of development.

Isobutene production can also support a transition to 100% BioLPG, benefiting from existing sugar beet supply chains in Eastern England. This pathway is expected to be proven by Global Bioenergies in the mid-2020s.

Transport is currently by far the highest value market for BioLPG suppliers, mainly due to financial incentives provided by the RTFO in the form of RTFCs. BioLPG is not an eligible fuel for receiving RHI support in domestic and non-domestic heating applications, meaning that suppliers are only able to market it at the same price as its fossil alternative, unless an end-user is willing to pay a price premium. An indication of additional revenues for supplying BioLPG in transport can be found below.



It is important to note that the non-inclusion of BioLPG as an eligible fuel for receiving payments as part of heat/process heat support schemes is a missed opportunity, as it would encourage the establishment of supply chains in non-transport markets, with multiple benefits, which are presented in detail in chapter 1.

Indicative actions required for the development of an indigenous BioLPG production include:

1. Engaging with UK oil refineries to develop production lines that co-process sustainable bio-oils with petroleum intermediates for the production of HVO diesel and BioLPG.
2. Securing a sustainable bio-oil feedstock supply from global markets at a reasonable price.
3. Investing in Research and Development of gasification and catalytic synthesis processes that target BioLPG as a main product.
4. Investigating whether there is any blend limit on using of isobutene in existing LPG supply networks and end-use infrastructure.
5. Engaging with policy makers so that BioLPG uptake in the off-gas grid buildings will be a priority in future UK policy support schemes.
6. Proving that BioLPG production is the best use of feedstock, by highlighting the benefits of HVO diesel over FAME, or by demonstrating that treating residual waste using the gasification technology, can potentially result in added value compared to incineration.

1 BioLPG has a key role to play for the UK to meet its net zero target

Key findings

- The Climate Change Act commits the UK government to bring all greenhouse gas emissions to net zero by 2050, compared with the previous target of at least 80% reduction from 1990 levels.
- Even in the most ambitious decarbonisation scenarios, there is still a residual gas demand which allows a significant role for green gases, mainly in the provision of heat in hard-to-decarbonise sectors.
- Bio-LPG has a key role to play, particularly, for rural sites that are off-the gas grid, where electricity grid capacity is limited and the use of high carbon emission fossil fuels for space and water heating is far more common.
  - BioLPG is chemically identical to fossil LPG, being 100% compatible with existing supply networks and end-use infrastructure.
  - In comparison to biomethane and hydrogen, BioLPG liquefies at a lower pressure at room temperature, which allows its cost-effective distribution and storage in off-gas applications.
  - BioLPG results in substantially reduced carbon, PM, and NOx emissions compared to solid and liquid fossil fuels.
- A variety of technological solutions, over a pure electrification pathway, are required to meet diverse heat needs in off-grid rural areas.
  - Heat pumps could be less effective when it comes to old or historic buildings that are less energy efficient due to the low temperature of heat that is typically provided.
  - In rural areas that are not densely populated, the increased use of electricity will likely require significant infrastructure upgrades, which might not be deemed cost effective by National Grid or the local distributors.
  - For some buildings of heritage value, the installation of external wall insulation would damage the appearance of the building
  - Creating the ideal environment for heat pumps comes at a cost, which when combined with their significantly higher CAPEX, compared to an LPG boiler, can be prohibitive.
  - An electrical solution is not suitable for processes that require high-temperature direct heating or where LPG is used in non-energy applications.
- A mixed technology approach, which includes the introduction of BioLPG on the heating market in off-grid rural areas will result in a significantly lower aggregate consumer cost compared to a purely electric pathway and substantial GHG emission savings (ca. 90%)
- The CCC acknowledges the key role of BioLPG in the decarbonisation of the heat sector. In its technical report on achieving net zero, BioLPG was used as the model fuel for hybrid heat pump systems in properties not suitable for full electrification.

The Climate Change Act commits the UK government by law to reduce greenhouse gas emissions by at least 100% of 1990 levels (net zero) by 2050 and was recommended by the Committee on Climate Change (CCC), which is the UK's independent climate advisory body. This target requires the UK to bring all greenhouse gas emissions to net zero by 2050, compared with the previous target of at least 80% reduction from 1990 levels.

Although electrification is expected to be the most widely adopted solution for the UK government to meet its net zero target, even in the most ambitious decarbonisation scenarios developed by recognised organisations, such as the CCC [1] and the National Grid [2], there is still a residual gas demand which allows a significant role for green gases, mainly in the provision of heat in hard-to-decarbonise sectors. For those on the gas grid, where there is continued use of natural gas, biomethane provides a realistic decarbonisation pathway, whereas bio-LPG has a key role to play, particularly, for sites that are off-the gas grid and for applications that are not suitable for an electrical solution.

1.1 The benefits of BioLPG in rural off-gas heating applications

UK households that are not connected to the gas network use different heating methods depending on whether the household is in a rural or urban setting (Figure 1).

In urban areas, properties are typically more energy efficient (newly-built) and predominately serviced by electrical heating, meaning that the most appropriate decarbonisation route appears to be reducing emissions of the power supply and lowering the heating demand by the use of more efficient heating measures, such as the installation of heat pumps.

In rural settings, the use of high carbon emission fossil fuels for space and water heating is far more common (figure 1), as domestic buildings are typically larger, older, less energy efficient, and located in remote areas where electricity grid capacity is limited. Cavity walls are also less prevalent than in the wider building stock, with almost 50% [3] of the rural off-gas grid buildings having solid walls that are more challenging to achieve an acceptable insulation standard. These characteristics make their electrification more difficult and expensive, and therefore green gases, and particularly BioLPG, can offer a suitable decarbonisation solution.

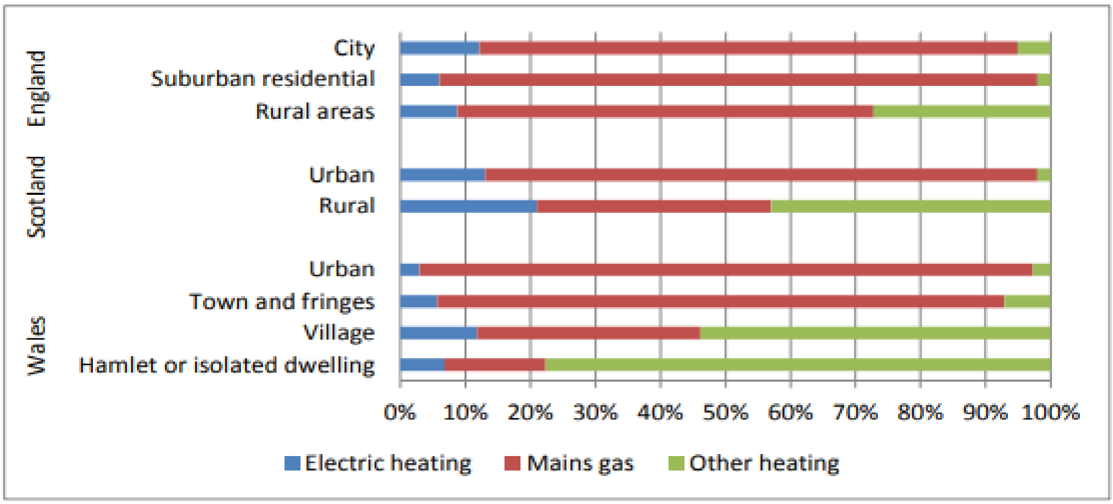


Figure 1: Main heating fuel by location in Great Britain [4]

A key feature that makes BioLPG a particularly suitable option for the decarbonisation of off-grid heating is its ability to liquefy at a relatively low pressure at room temperature, which allows its cost-effective distribution and storage as a high energy density liquid fuel. In comparison, biomethane and hydrogen need to be cooled to a much lower temperature in order to be turned to a liquid [5], that can be stored in a tank of the same size corresponding to prohibitive costs. Therefore, BioLPG can be considered as the ideal decarbonisation solution, amongst the available green gases, in areas where the delivery of gaseous fuels through pipelines is not an option.

As a side note, there are also a range of bioliquids that could in theory be used in off-gas grid heating applications, including biodiesel, pyrolysis oil, and waste vegetable oils. However, none of these bioliquids can be considered as a drop-in replacements in the current fossil pool, as they are restricted either by blend limits or by the requirement of substantial boiler conversions.

Bilans-GES's resource centre for greenhouse gas accounting estimates the carbon intensity of BioLPG to be 0.0603 kgCO2/kWh, which results in significant GHG savings compared to fossil heating oil and fossil LPG (figure 2), based on the data presented in Appendix 1. However, this value should be viewed as an indicative figure, as the resultant Carbon Intensity (CI) of the fuel is highly dependent on the feedstock and technology used in its production. Based on the experience of NNFCC reviewing real carbon intensity values, slightly lower GHG savings are expected for BioLPG derived from virgin vegetable oils like Palm Oil through the HVO pathway. Nevertheless, figures examined show that savings can be boosted to over 80%, or even approach 90%, when using UCO and renewable hydrogen as feedstock or by utilising advanced thermal conversion technologies.

Interestingly, wood boilers appear to have the best GHG performance, but as shown in figure 3, they emit significant quantities of air pollutants, resulting in a higher aggregated cost for the consumer, as shown in Appendix 2.

It is important to note that hardly any decarbonisation alternative can be considered as a net zero solution. The net zero target implies that any emissions have to be balanced by offsetting an equivalent amount of greenhouse gases from the atmosphere, through planting trees or purchasing negative CI electricity acquired through carbon capture and storage technologies.

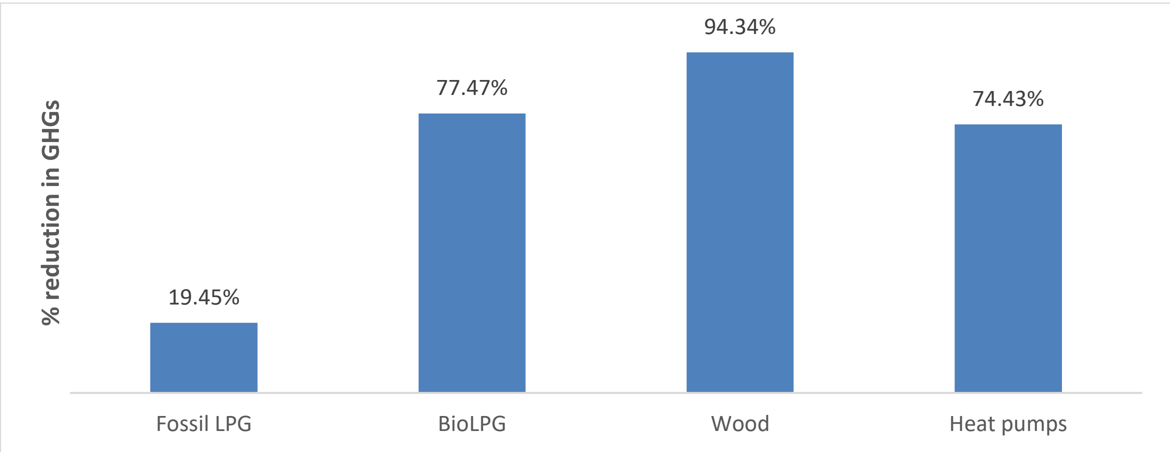


Figure 2: Heating footprints – heating oil versus competing fuels (based on data provided in Appendix 1)

Emissions of air pollutants (NO_x, PM_{10}, and $PM_{2.5}$) from biopropane heating systems are expected to be the same as for fossil LPG, although the lifecycle GHG emissions are reduced. LPG is a gas at the point of combustion and therefore emissions of air pollutants are significantly lower than heating oil and solid fuels, as shown in figure 3. Therefore, in addition to the GHG emission savings, the wider adoption of LPG and BioLPG can improve the air quality significantly, especially for cities but even in rural areas where there does not appear to be such a significant air quality issue.

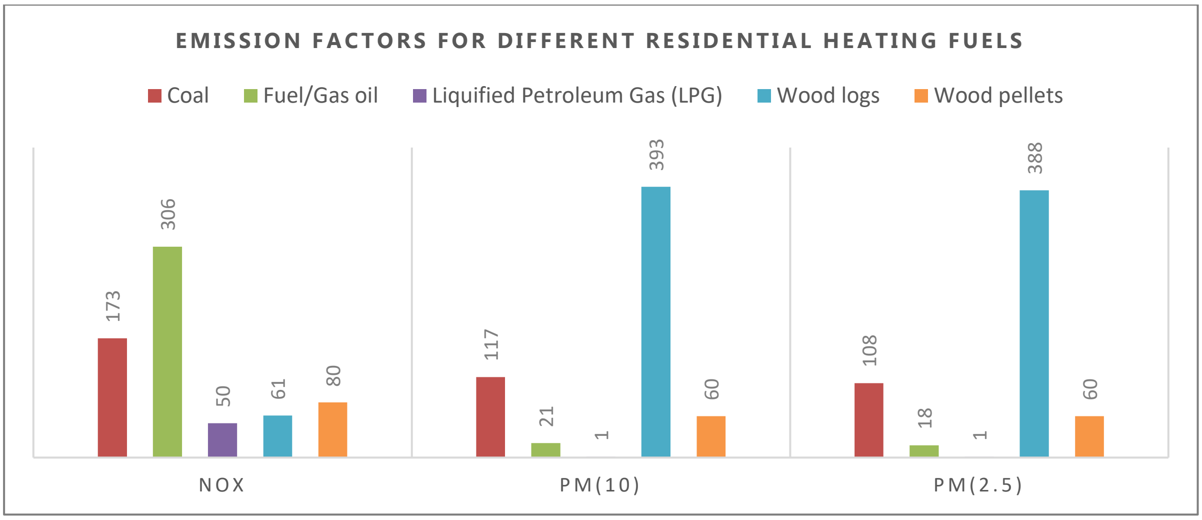


Figure 3: Comparison of emission factors for different residential heating fuels [6]

1.2 The limitations of heat pumps

While heat pumps can offer a suitable decarbonisation solution for heating modern buildings that are characterised by their high energy efficiency performance, they could be less effective when it comes to old or historic buildings that are less energy efficient due to the low temperature of heat that is typically provided.

Even though the electric heat pump, when operated under the claimed system efficiency, appears to have the lowest levelized cost among different heating systems (Appendix 2-High-stated efficiency HP figure), operating a heat pump system in a non-ideal environment (e.g. buildings with solid walls and low levels of thermal insulation) which is less suited to constant low temperature, will result in significantly lower efficiencies and a higher aggregated cost for consumers compared to using of an LPG boiler that operates with no such issues (Appendix 2-Typical in-situ HP figure).

Creating the ideal environment for heat pumps comes at a cost, which when combined with their significantly higher CAPEX, compared to an LPG boiler, can be prohibitive. Buildings that are currently oil-heated typically have solid-walls, that are more challenging to achieve an acceptable insulation standard when compared to cavity walls. While for some buildings of heritage value, the installation of external wall insulation would damage the appearance of the building [7].

There is an additional aspect regarding the wider roll out of heat pumps on the electricity distribution network. Particularly in rural areas that are not densely populated, the increased use of heat pumps will likely require significant infrastructure upgrades, which might not be deemed cost effective by National Grid or the local distributors.

Finally, heat pumps or any other electrification alternatives are not suitable decarbonisation options for processes that require high-temperature direct heating (e.g. melting of raw materials, extrusion, and moulding) or where LPG is used in non-energy applications (e.g. production of chemicals).

1.3 A mixed technology approach

The opportunities and challenges afforded the consumer when switching to a low carbon heating system, differ depending on the type of the user and the market sector. Therefore, a variety of technological solutions are required to meet diverse heat needs in off-grid rural areas.

In the case of rural off-grid homes, a recent study conducted on behalf of Liquid Gas UK, reveals that a mixed technology approach, which includes the introduction of BioLPG on the heating market, has a significantly lower aggregate consumer cost compared to a purely electric pathway and at the same time can deliver substantial GHG emission savings (90%); aligning strongly with the net zero targets [7].

Based on the results of this study, older homes that make up just over half of the housing stock in rural off-gas grid locations in the UK, may face a significant cost increase of about 37% through a pure electrification pathway when compared to a mixed technology approach with a significant inclusion of BioLPG[1]. Factors that contribute to this additional cost include:

1. Further investments required to the electricity distribution network to support higher demand.
2. Additional renewable power generation needed to meet peak heat demands.
3. Older homes are larger and typically not energy efficient and therefore use more energy than a more modern house insulated to the current standard.

An additional point to be considered is that a mixed technology approach, with an inclusion of LPG in the short term and BioLPG in the mid-term, can allow faster progress to be made towards meeting the decarbonisation targets, with one major benefit being the link to the existing LPG supply chain network with knowledge of boiler and general housing installations to the most current standards[2].

The CCC also acknowledges the benefits of a mixed technology approach and the key role of BioLPG in the decarbonisation of the heat sector. In its technical report on achieving net zero, BioLPG was used as the model fuel for hybrid heat pump systems in properties not suitable for full electrification [8]. Those systems typically combine an electric heat pump with a backup boiler to operate during peak heat periods in winter. However, it should be recognised that the upfront cost of these systems is high, considering the homeowner is required to buy a heat pump and replace existing boilers with low carbon alternatives.

[1] Even though the scope of this study considers the wider UK case, the results are expected to be valid in the case of Scotland as well.

[2] This is of particular importance for Scotland as they have to meet their net zero target 5 years ahead of the rest of the UK, with demanding interim targets. Scotland's Climate Change Plan sets out a challenging trajectory requiring 35% and 70% of domestic and non-domestic buildings respectively, to be supplied by low carbon heat technologies by 2032, with further reductions towards 2045 [86].

2 Policies that incentivise BioLPG production in the UK

Key findings

- This chapter gives an overview of the main support mechanisms that encourage the production and use of sustainable fuels in the transport and heat markets and highlights those that incentivise the uptake of BioLPG.
- Transport is currently by far the mostly incentivised market for BioLPG and is expected to remain such until 2032 and possibly beyond, due to the presence of the RTFO order.
  - Under the RTFO, BioLPG is awarded 1.75 Renewable Transport Fuel Certificates (RTFCs) per kg of fuel which is supplied for use in a transport application
  - The number of certificates is doubled to 3.5 RTFCs per kilogram of BioLPG for certain double counting feedstocks such as sustainable wastes.
  - RTFCs can be traded in the open market to transport fuel suppliers who need to provide a volume of sustainable renewable fuel to meet their obligation.
- BioLPG is not an eligible fuel for receiving RHI support in domestic and non-domestic heating applications.
  - The RHI scheme comes to an end on 31 March 2022, with the future support for low carbon heat being the subject of a number of policy reviews at the time of writing.
- The consultation on 'Future Support for Low Carbon Heat' ended on the 7th July 2020 and set out proposals for:
  - A Clean Heat Grant: support for heat pumps and in certain circumstances biomass, through an upfront capital grant to help address the barrier of upfront cost.
  - A Green Gas Support Scheme (GGSS): increasing the proportion of green gas in the grid through support for biomethane injection.
- The Clean Heat Grant scheme does not provide grant support on the type of hybrid heat pump systems recommended by the CCC that combine an electric heat pump with a backup LPG boiler
  - BEIS recognises the high potential of hybrid system towards the decarbonisation of off-gas grid buildings and will continue to consider their role in the future.
- The Green Gas Support Scheme will be limited to biomethane produced by anaerobic digestion (AD) for injection to the grid and will be introduced and run between autumn 2021 and 2025/26.
  - BEIS recognises in the longer-term, it may be appropriate to extend support to injection of other sources of green gas, such as hydrogen, but any such decisions would be subject to future consultation.
  - This may not be of interest to LPG suppliers, as LPG supply chains are ideally suited to operate outside the grid.
- A separate consultation on proposals for a regulatory framework on Off-Grid heating options to phase out the installation of high carbon fossil fuel heating in new and existing buildings will be published in the second half of 2020.
- The decarbonisation of industrial processes will be supported by the Industrial Energy Transformation Fund (IETF)
  - BioLPG production and use in industrial settings is not expected to be an eligible technology for receiving support

2.1 Transport

At the current time, transport is by far the mostly incentivised market for BioLPG and is expected to remain such until 2032 and possibly beyond. The Renewable Transport Fuel Obligation (RTFO) [9] includes an increasing volume of transport fuels until 2032 when the current increase levels plateau. Even if no more increases were deemed necessary in 2032 the current inclusion volumes would remain valid in law, applying to all the UK nations, until the law is rescinded.

Under the RTFO, which is presented in more detail in Appendix 3, BioLPG is awarded 1.75 Renewable Transport Fuel Certificates (RTFCs) per kg of fuel which is supplied for use in a transport application. For non-obligated bodies, these certificates can be traded on the open market to obligated fuel suppliers, who are mandated to supply specific volumes of sustainable fuels, calculated as a proportion of the overall volume of fuel they supply to the transport market. The number of certificates is doubled to 3.5 RTFCs per kilogram of BioLPG for certain double counting feedstocks such as sustainable wastes.

Table 1: Types, number, and prices of RTFCs for different feedstock.

Feedstock	BioLPG production Technology	RTFCs type	Certificate prices*	Buy-out price	Number of certificates per kg of bioLPG [10]
Virgin vegetable oils	HVO	cRTFCs	0.275	£0.30	1.75
Cat. 2&3 animal fats	HVO	General	0.2859	£0.30	1.75
Cat. 1 animal fats	HVO	General	0.2859	£0.30	3.5
Waste cooking oils	HVO	General	0.2859	£0.30	3.5
Woody Biomass (sustainable waste-residues, short rotation coppice)	ATC	General	0.2859	£0.30	3.5
Woody biomass (other)	ATC	General	0.2859	£0.30	1.75
MSW/RDF (biomass fraction)	ATC	General	0.2859	£0.30	3.5
MSW/RDF (non-biomass fraction)	ATC	Not eligible	-	-	-
Renewable component of end-of-life tyres	ATC	General	0.2859	£0.30	3.5
Fossil component of end-of-life tyres	ATC	Not eligible	-	-	-
Glycerol	Dehydration	General	0.2859	£0.30	1.75

* Price data from: Energy Census [11], London, 29 May 2020

Three categories of RTFC's are issued: 'relevant crop', 'development fuel' and 'general' RTFCs, depending on whether biofuels are produced from feedstocks that are subject to a 'crop cap' or the end fuel meets the eligibility criteria for development fuels, presented in figure 26 of Appendix 3. RTFCs awarded to all other renewable fuels are labelled as 'general'. Table 1 presents the types and number of certificates that can be redeemed per kilogram of BioLPG supplied in the UK market for different feedstock and technology combinations. BioLPG does not meet the eligibility criteria for development fuels.

Additional incentives for supplying BioLPG in the transport market are currently provided by the 'Motor Fuel Greenhouse Gas Emissions Reporting' Regulation [12] in the form of GHG credits, but currently the obligation to report GHG emissions against a reduction target ends in December 2020.

GHG credits are awarded to each kg of CO_{2eq} saved, for fuels that have a GHG intensity below the GHG target level for the relevant year (88.45 gCO2e/MJ for 2020)[3]. As a result, considering 2020 as a reference year, 1 tonne of BioLPG with an indicative Carbon Intensity (CI) of 0.0603 kgCO_2/kWh (16.6 g CO_2/MJ), would be eligible for 3,305 GHG credits, the price of which was reported by Energy Census to be 2.75 pence per certificate at the 29th May 2020.

GHG credits can be traded by companies that supply low-carbon fuels to the ones that predominately supply high carbon fossil fuels, such as diesel and petrol, and for the latter to meet their GHG reporting obligation.

2.2 Residential and commercial heating

The Renewable Heat Incentive (RHI) is currently the main support mechanism that encourages renewable heat production and use in England, Scotland, and Wales, by offering fixed tariffs to owners of a low carbon heat installations, but BioLPG heating systems are not eligible for this type of support[4].

The RHI scheme comes to an end on 31 March 2022, with the future support for low carbon heat being the subject of a number of policy reviews at the time of writing. The consultation on 'Future Support for Low Carbon Heat' was published on 28th April 2020, setting out government proposals for a new Scheme [13], which will apply to England, Scotland, and Wales, but not to Northern Ireland. This consultation ended on the 7th July 2020 and set out proposals for:

1. A Green Gas Support Scheme (GGSS): increasing the proportion of green gas in the grid through support for biomethane injection.
2. A Clean Heat Grant: support for heat pumps and in certain circumstances biomass, through an upfront capital grant to help address the barrier of upfront cost.

The Green Gas Support Scheme will be limited to biomethane produced by anaerobic digestion (AD) for injection to the grid and will be introduced and run between autumn 2021 and 2025/26. However, BEIS recognises in the longer-term, it may be appropriate to extend support to injection of other sources of green gas, such as hydrogen, but any such decisions would be subject to future consultation. This may not be of interest to LPG suppliers, as LPG supply chains are ideally suited to operate outside the grid, it should also be noted that BioLPG injected to the grid cannot be recovered as BioLPG, due to the large costs of separation from the methane and other gases present on the gas grid.

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[3] Obligated fuel suppliers must achieve a reduction in life cycle GHG emissions from the fuel they supply of 4% in 2019 and 6% in 2020, compared to the EU fossil fuel baseline of 94.1gCO2e/MJ.

[4] In Northern Ireland, a similar incentive was available, the 'Northern Ireland Renewable Heat Incentive', launched for the non-domestic sector on 1st November 2012 supporting biomethane injection at all scales, biogas combustion up to 200kWth and biogas CHP. This scheme was suspended for new applications on 29th February 2016, but like the one in Great Britain, BioLPG is not an eligible fuel for receiving support.

Support through the Clean Heat Grant will be targeted at households and small non-domestic buildings, to enable the installation of heat pumps and, in limited circumstances, biomass, to provide space and water heating. Although BEIS does not propose to exclude support for heat pumps on gas grid, they expect uptake to be higher in off gas grid areas.

Even though there is no provision for grants for new BioLPG heating systems, the capital cost of LPG boilers is around 7 to 10 times lower than heat pumps and biomass heating systems respectively (Appendix 1), and this scheme is designed to provide support only on technologies with high upfront costs.

The Clean Heat Grant scheme does not provide grant support on the type of hybrid heat pump systems recommended by the CCC that combine an electric heat pump with a backup LPG boiler to operate during peak heat periods in winter. BEIS recognises the high potential of hybrid system towards the decarbonisation of off-gas grid buildings and will continue to consider their role in the future, but they argue that there is no sufficient evidence available on how they perform in practice in off gas grid installations.

A separate consultation on proposals for a regulatory framework on Off-Grid heating options to phase out the installation of high carbon fossil fuel heating in new and existing buildings will be published in the second half of 2020.

2.3 Process heating

While process heating has been eligible for support under the Non-Domestic RHI, it is not included in the scope of the new Clean Heat Grant, the purpose of which is to provide targeted support for space and water heating in residential and commercial buildings. The decarbonisation of industrial processes will be supported by the Industrial Energy Transformation Fund (IETF), which will provide an overall grant support of £315 million in energy efficiency and deep decarbonisation projects, such as industrial carbon capture, and low-carbon fuel switching. A consultation was also published on 10 October 2019 [14], seeking views to finalise the design of the fund, and at the time of writing, the UK government is analysing the feedback received.

The IETF will be delivered in two phases.

1. **Phase 1** will launch in 2020, and will be worth up to £30 million, providing support for feasibility and FEED studies for the deployment of energy efficiency projects (minimum award per project: £1 million)
2. **Phase 2** will deliver the full scheme from 2021 to 2024, including deep decarbonisation projects, and will be worth around £285 million. This support is for technologies that are either ready for demonstration in an operational environment or ready for deployment (at TRL 7 or higher), with the aim being to show that the technology can be proven to work in industrial settings and that any associated risks can be managed.

It should be noted that in the proposal document, "deep decarbonisation" refers to measures beyond efficiency that reduce industrial process emissions, using a) Industrial carbon capture, b) Fuel switching (Low carbon hydrogen, Electrification, and Biomass), and c) Material efficiency. To the best of our understanding, BioLPG production and use in industrial settings is not expected to be an eligible technology for receiving support, but the final design of the fund, including which technologies will be eligible for support, has not been published at the time of writing.

2.4 The role of Local Enterprise Partnerships in England

LEPs are partnerships between local authorities and businesses and play a central role in bringing together business interests to decide on regional economic development priorities. There are 38 Local Enterprise Partnerships across England, presented in Appendix 4, each of which is responsible for implementing the strategic objectives of central government, which are transcribed into local strategic documents. These currently include:

1. **Regional economic strategies** which identify the strengths of the LEP area, the challenges to growth and the actions that the LEP will undertake with partners to address these challenges.
2. **Local industrial strategies** – aligned to the National Industrial Strategy for which the LEPs are key delivery partners.
3. **Low carbon strategies** – aligned to the objectives of the national clean growth strategy

LEP's are also responsible for supporting delivery of European Structural and Investment Funds through the ESIF Growth Programme in England (2014-2020), which has provided funds to stimulate growth in local areas, supporting investment in innovation, businesses, skills and employment. Within the ESIF, the 'European Regional Development Fund' (ERDF) has been important in promoting research and innovation as well as the adoption of low carbon technologies in all sectors, including transport and buildings[5] [15]. In addition, LEPs have access to grant and loan funding to encourage and support eligible new businesses, particularly SME's, through applications to the Government's 'Regional Growth Fund' [16].

BioLPG project developers may contact the local hubs of their interest, to guide their investment decisions, in terms of whether their plans are in line with local strategies or whether they are eligible for any type of financial support.

2.5 Additional funding opportunities available on a devolved basis

In the case of Scotland, energy projects, that facilitate transition to a low carbon economy and fit with the Scottish Government's Energy Strategy, can receive funding support, in the form of flexible loans and equity investments, from the Energy Investment Fund ('EIF'), managed and delivered by the Scottish Investment Bank. Even though funding was allocated until 31 March 2020, new projects seeking support are encouraged to discuss their options directly with the EIF team. It should be noted that EIF does not provide full project funding, but it is designed to fill funding gaps and give

[5] With Britain's Exit from the EU, it is expected that the types of work previously supported by 'EU Structural Funds' will be supported through the 'UK Shared Prosperity Fund'.

confidence to private lenders to invest in low carbon energy projects. The EIF is not available for R&D, feasibility, or pre-development costs[6,7].

Potential funding opportunities in each devolved administration are presented in Appendix 5. The eligibility of BioLPG projects in each of these funding mechanisms needs to carefully be examined

[6] The Scottish Government's Community and Renewable Energy Scheme (CARES) also offers a range of financial support to local energy projects, which demonstrate financial and social benefits to local community, including the alleviation of fuel poverty and jobs creation. However, Local ownership and/or community involvement must be at the heart of projects supported. Eligible applicants include constituted non-profit community groups, charities, faith groups, academic institutions, local authorities, housing associations and small to medium sized rural businesses [87].

[7] Scottish-based Low Carbon Heat projects could also submit bids for match-funding from the Low Carbon Infrastructure Transition Programme (LCITP), but this programme is now closed to new applications. To the best of our knowledge, there are no plans to extend or replace this scheme [88].

3 BioLPG production options

Key findings

- This chapter gives an overview of the most promising BioLPG production technologies and their development status. Technologies with limited production potential are also presented in Appendix 6.
- Hydrogenation of triglycerides (vegetable oils and fats) is currently the only process to produce bio-propane that is operating at commercial scale.
    - HVO diesel is produced as the main product and can be used directly in existing diesel engines without modification
    - Bio-propane rich off-gases are produced as a by-product at a ratio of around 50 kg per tonnes of HVO diesel. Pure bio-propane can be recovered from the off-gas stream, which is chemically identical to conventional LPG and suitable for LPG boilers.
- There are two models for hydrotreating triglycerides:
    - The development of dedicated production units (hydrogenators) that operate exclusively using bio-based feedstocks.
    - The co-processing of bio-oils and fossil oils in existing petroleum refineries.
- Gasification based pathways can potentially lead to the production of significant BioLPG quantities.
- The gasification process converts any carbonaceous material to syngas that can be upgraded to produce a variety of products. Upgrading steps that are relevant to BioLPG production include:
    - Conventional Fischer-Tropsch synthesis - small volumes as by-product
    - Syngas-to methanol-to BioLPG – main product
    - Direct BioLPG synthesis – main product
- The syngas-methanol-DME-BioLPG route is the mostly developed gasification pathway to produce BioLPG as a main product.
    - the fully integrated process has not been demonstrated in commercial scale facilities yet.
    - the individual technical processes employed appear to be mature and are being used widely in commercial applications.
- More work is required to demonstrate that commercially viable routes are feasible in the case of direct synthesis.
- Fermentation of sugars can also lead to the production of bio-based isobutene that can be mixed with conventional LPG.
- The most promising isobutene production process through fermentation appears to be the 'IBN-One', developed by Global Bioenergies.
    - converts sucrose into isobutene using genetically engineered microorganisms
    - proven at a demonstration facility in Germany, which can produce 150 tonnes of final product per year.
    - a commercial-scale facility is expected to be commissioned in 2022 in collaboration with Crystal Union
- Global Bioenergies has expressed interest in entering the LPG market, by demonstrating the feasibility of blending isobutene into domestic bottled gas (LPG)

3.1 Hydrogenation of bio-oils

Currently the only process for the production of biopropane that is operating at commercial scale is the hydrogenation of triglycerides such as virgin vegetable oils, fats, and used cooking oils. This process involves the reaction of triglycerides with hydrogen at elevated temperatures in the presence of catalysts to hydrogenate the double bonds in the fatty acid chains in the triglyceride. The glycerol backbone is also broken as shown in figure 4, leaving paraffinic n-alkanes – which is the HVO diesel – and the hydrogenated three-carbon backbone, biopropane.

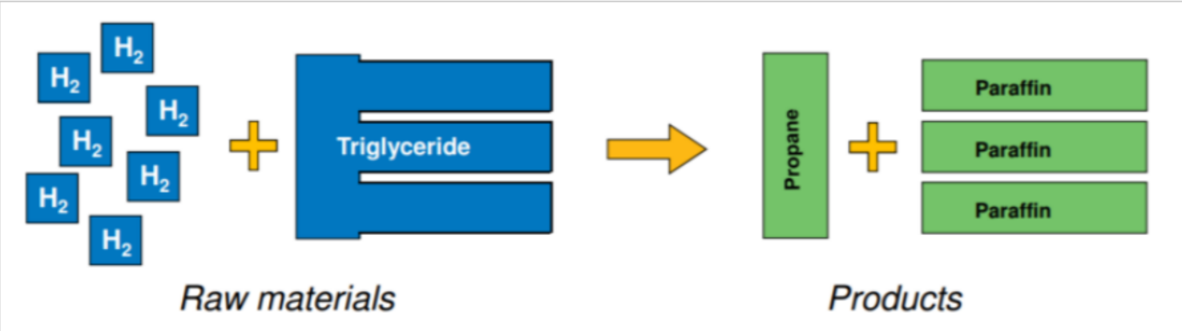


Figure 4: A schematic overview of the HVO process [17]

HVO diesel is the main product and can be used directly in existing diesel engines without modification, but the process can be tailored to produce a fuel meeting the specifications for use in commercial aircraft. Bio-propane rich off-gases are also produced as a by-product at a ratio of around 50 kg per tonnes of HVO diesel [18]. Pure biopropane can be recovered from the off-gas stream, which is chemically identical to conventional LPG and suitable for LPG boilers.

There are two models for hydrotreating triglycerides (vegetable oils and fats):

1. The development of dedicated production units (hydrogenators) that operate exclusively using bio-based feedstocks.
2. The co-processing of bio-oils and fossil oils in existing petroleum refineries (figure 5).

In the co-refining model, there is a limit to the amount of bio-oils that can be blended with petroleum intermediates, which appears to be around 30%. After this point significant changes in the storage and processing infrastructure are expected to be required.

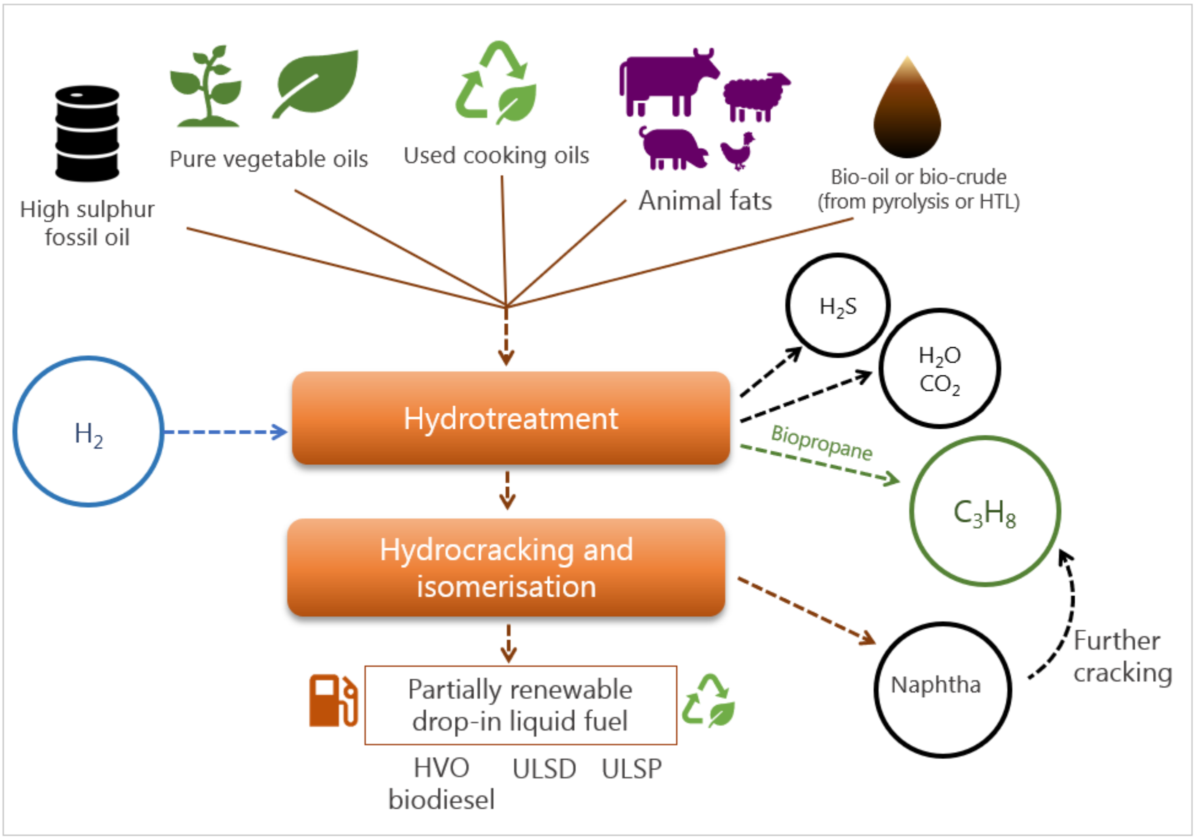


Figure 5: Coprocessing of bio-based and fossil feedstock in existing oil refineries

Pyrolysis oil can also be blended with petroleum intermediates to produce certain amounts of BioLPG. Even though trace amounts of bio-propane are present in off-gases of a pyrolysis plant, most of the fuel produced via this route comes from the co-refining stage. Unlike vegetable oils (triglycerides) where bio-propane is produced during the hydrogenation step, in the case of pyrolysis oil BioLPG is produced during the hydrocracking step, where long-chain hydrocarbons are broken for the production of a range drop-in fuels (there is not a glycerol component like in the case of vegetable oils and fats). According to Atlantic Consulting, BioLPG yields from pyrolysis oil processing are expected to be relatively low, about 1 to 2%.

3.1.1 Development status

HVO technology is mature and widely tested – it was launched by Neste in 2008 and is now used across the world. Figure 6 presents global HVO diesel production volumes by plant type in 2018 as well as a forecast up to the year 2024. Based on IEA's estimates, the global Hydrotreated vegetable oil (HVO) production is set to more than double from around 5.5 billion litres in 2018 to 13 billion litres in 2024 [19][8]. Interestingly, despite the significantly higher CAPEX and implementation difficulty compared to co-processing, most of the companies decide to invest in pure HVO production plants. Currently, the co-production capacity is estimated at 0.48 billion litres in 2020 and is expected to stay at that level by 2022, as no major investments have been announced.

[8] Additional projects are included in the accelerated case, but they are at an early stage of development. Their delivery would boost HVO production to around 17 billion L by 2024.

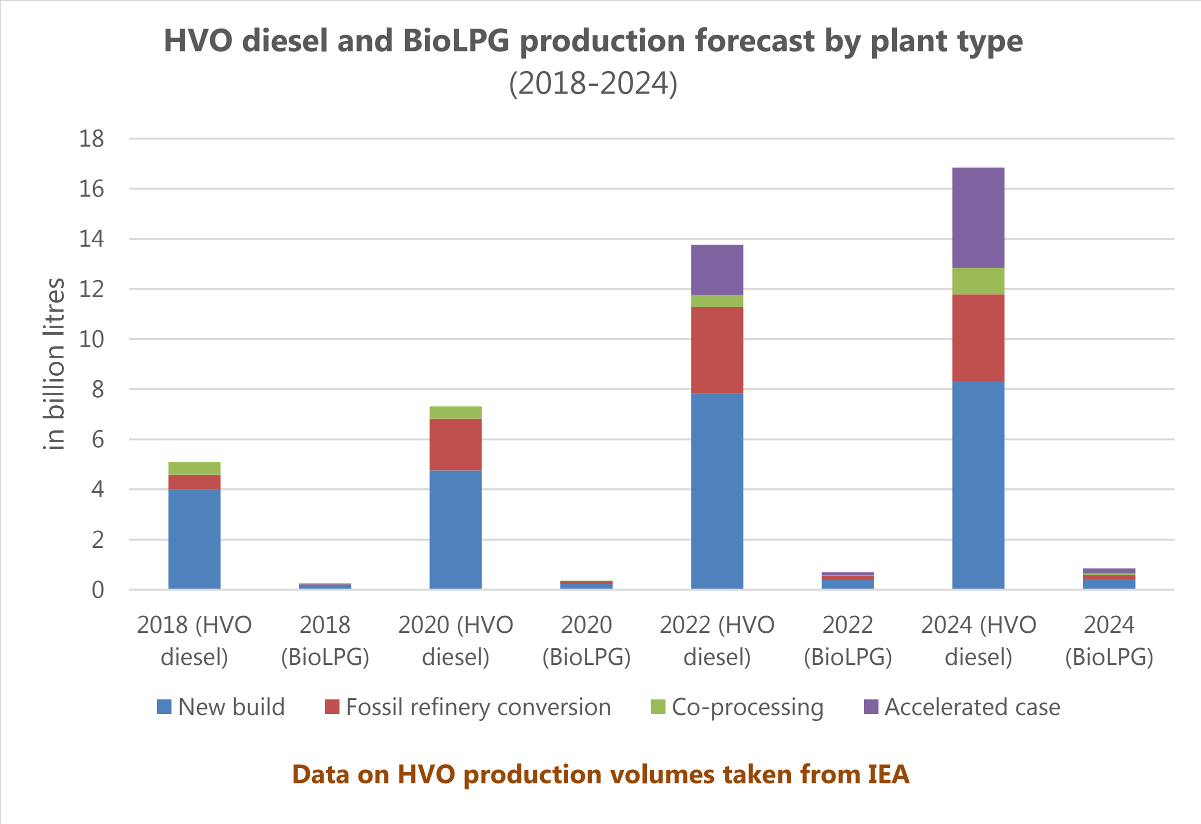


Figure 6: HVO diesel and BioLPG production forecast by plant type. [19]

The BioLPG production potential has been estimated based on HVO diesel production volumes. However, few developers currently recover pure biopropane from the off-gases stream, and therefore these figures indicate the overall production potential rather than actual production quantities that meet LPG specifications.

3.1.2 Competitiveness of HVO diesel

A factor that can determine the potential of this technology in the UK is the demand for renewable diesel, which is primarily driven by the RTFO order. Sufficient demand is expected for renewable diesel that can be classified as 'development fuel' (on this occasion mainly produced using pyrolysis oil as feedstock). This is because at the current time, there is no confidence in the market that there would be adequate fuel supply in the short to mid-term for meeting the development fuel targets (table 3). There is always the risk of high competition from other fuels, such as hydrogen, as the UK currently provides by far the highest incentives for this type of fuels. However, as mentioned above, refineries are able to change their feedstock mix in response to market movements.

In the case of renewable diesel produced using UCO and tallow as feedstock, although the biofuels market appears to be saturated, the UK demand for waste derived transport fuels will increase from 5.6 to 7.6% between 2020 and 2032 (table 3), while there are also opportunities to replace some biodiesel quantities currently imported from overseas; around 74% of the biodiesel supplied in the UK market is imported from overseas, based on RTFO statistics [20].

Table 2: Renewable Transport Fuels Obligation Target

Year	Total %	Crop %	Waste %	Development %
2019	8.5	4	4.4	0.1
2020	9.75	4	5.6	0.15
2021	10.1	4	5.77	0.5
2022	10.4	3.67	5.93	0.8
2023	10.6	3.5	6.1	1
2024	10.8	3.33	6.27	1.2
2025	11	3.17	6.43	1.4
2026	11.2	3	6.6	1.6
2027	11.4	2.83	6.77	1.8
2028	11.6	2.67	6.93	2
2029	11.8	2.5	7.1	2.2
2030	12	2.33	7.27	2.4
2031	12.2	2.17	7.43	2.6
2032	12.4	2	7.6	2.8

An additional point to consider is that the HVO production process can be tailored to produce a fuel meeting the specifications for use in commercial aircraft. This is of utmost of importance as the kerosene market segment is projected to grow in the EU in the next 10 years, while during the same period, diesel use is expected to decline due to the introduction of hybrid and electric vehicles [21]. From 15 April 2018, renewable fuel used in aviation in the UK is also eligible for reward under the RTFO, although fossil aviation fuel is not obligated.

3.2 Gasification-based pathways

Gasification is a process that is typically conducted at temperatures of 800-900°C, and uses a controlled volume of pressurised air, oxygen, or steam to convert any carbonaceous material to a low to medium energy gas known as syngas (with small amounts of char formation). Syngas can either be combusted for heat and power or upgraded to produce a variety of products. Upgrading steps that are relevant to BioLPG production are presented below:

1. Conventional Fischer-Tropsch synthesis

The Fischer-Tropsch process was developed as a means of producing liquid hydrocarbon fuels from syngas using a range of different 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 some shorter carbon chain molecules (gasses) as by-products, which may contain propane and butane.

Project developers typically design production plants to use this off-gas stream as part of their process fuel. Still, there is the option to recover the propane and butane components for the production of a fuel that meets LPG specifications, but the resulting quantities are expected to be very low. Therefore, this pathway will not be further investigated as part of this report.

2. Syngas-to methanol-to BioLPG

Contrary to conventional FT synthesis, this process has the ability to produce BioLPG as a primary product. It involves the conversion of syngas into methanol in the presence of a catalyst (usually copper-based), and then its dehydration to form dimethyl ether (DME) as intermediate, prior to the production BioLPG through hydrogenation.

It should be noted that DME is a colourless gas that can be blended with LPG at a level of up to 20%, 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. Therefore, the additional conversion cost has to be weighed against the benefits of producing BioLPG to justify further processing.

3. Direct BioLPG synthesis

Research reveals that the FT process can be altered to produce shorter carbon chains, focusing on BioLPG formulation [22] (around 50% of the total output by weight [17]), while evidence suggests that the BioSNG production process, which involves the gasification of carbonaceous materials and the catalytic conversion of syngas to synthetic natural gas, can also be modified to produce BioLPG [17].

3.2.1 Development Status

The syngas-methanol-DME-BioLPG route appears to be the mostly developed gasification pathway for the production of BioLPG, but to the best of our knowledge the fully integrated process has not been demonstrated in commercial scale facilities yet. However, the individual technical processes employed appear to be mature and are being used widely in commercial applications.

Methanol production using syngas from gasification is a well-developed and commercially practiced process by Enerkem, which has operated a gasification and methanol synthesis production plant in Canada since 2014. World production of DME today stands at approximately 5 million tons per annum, primarily by means of methanol dehydration, but it is currently not offered 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 [23]. The hydrogenation step is a widely used technique in oil refineries, but Japan's University of Kitakyushu has also developed a specific laboratory-scale process for the conversion of DME to LPG, validating that hydrogenation is a feasible approach [24]. Therefore, it is expected that the upgrading of syngas to produce BioLPG, with the intermediate production of methanol and DME, is achievable within the next decade using existing conversion technologies.

In the case of BioLPG direct synthesis, more work is required to demonstrate that commercially viable routes are feasible. BioSNG process modification is not expected to be technically challenging, but there is no indication that any significant research and development is being carried out at the time of writing. The alternative FT pathway, mostly developed by Japan Gas Synthesis Co. Ltd. and the University of Kitakyushu, appears to be at an early stage of development (possibly pilot scale). Demonstration in a larger scale to verify efficiencies and costs is required to determine the extent of the opportunity [25].

3.3 Fermentation of sugars

Fermentation of sugars can also lead to the production of bio-based isobutene that can be mixed with conventional LPG and potentially contributing to the decarbonisation of the Scottish heating sector; LPG mainly consists of propane and butane, but it can also include propene, butene and isobutene [26].

The most promising isobutene production process through fermentation appears to be the '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. Bioenergies have set up a joint venture with Crystal Union to build a commercial-scale facility in France, which is expected to be commissioned in 2022. The project is currently at the planning stage and is reported to produce up to 50,000 tonnes of isobutene per annum.

Isobutene is a major building block for the production of a wide range of chemicals, cosmetic ingredients, and fuels (figure 7). These markets may have an impact on the future 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 facility [27]. However, Global Bioenergies has also expressed interest in entering the LPG market, by demonstrating the feasibility of blending isobutene into domestic bottled gas (LPG) as well as its compatibility with the logistics chain and domestic appliances [28].

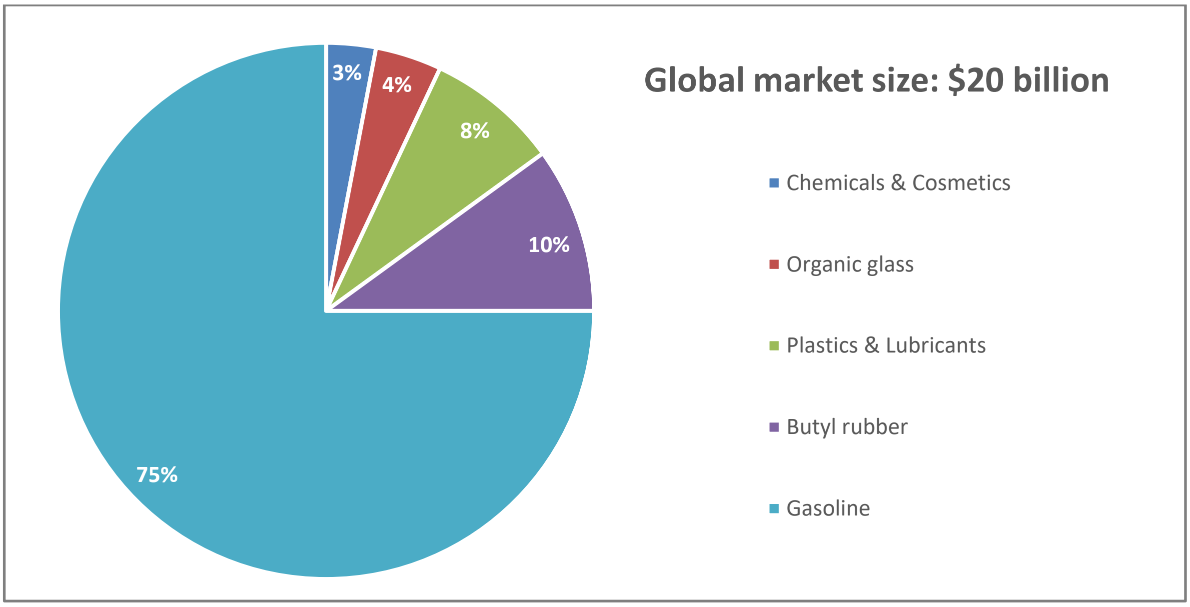


Figure 7: Existing isobutene markets [29]

4 BioLPG production opportunities in England

Key findings

- The development of domestic BioLPG production has an important role to play for England to meet its decarbonisation targets.
- England has a high proportion of users who are off the gas grid, with around 3.3 million residential properties not connected to the gas network
    - The total number of English residential properties that are currently using heating oil, LPG, and solid mineral fuels as their primary heating source is estimated to be about 1.1 million and define the scale of the opportunity.
    - Households that are already using LPG as heating fuel (around 147,000 in England) are the most obvious target market for BioLPG suppliers.
    - A recent study conducted on behalf of the UK government revealed that electric heating is not technically feasible in 10% of the 1.3 million rural off-gas dwellings in England and Wales.
- Around 62,000 non-domestic buildings are also heated with oil or LPG in England and Wales[3][3][3][3] and can theoretically define the scale of the opportunity for BioLPG suppliers in the English commercial heating sector.
- In the transport sector, LPG has been identified as having the potential to reduce pollutant emissions and as such could be considered for evaluation by local authorities as part of their Clean Air Zone planning.
- Gasification based pathways appear to have the highest potential for producing significant volumes of BioLPG in England, mostly through the valorisation of residual waste currently destined to landfills and RDF quantities exported.
    - Available RDF quantities alone could lead to the production of about 300,000 tonnes of a mixture of bio-LPG and fossil LPG (low carbon fossil fuel), which equates to about 30% of the current LPG demand in the United Kingdom.
- Fermentation of sugars to isobutene is another pathway with potential to support BioLPG production, as England is the only Nation in the United Kingdom with an active sugar refining industry.
    - Opportunities also exist for the production of second-generation isobutene, utilising agricultural residues (mainly straw), provided that lignocellulosic feedstock pre-treatment technologies will be cost-effectively deployed at a commercial scale.
- The 4 oil refineries located in England can also co-process very large volumes of bio-oils with petroleum intermediates for the production of BioLPG as a by-product, without reaching any blending limits.
    - this requires either the diversification of significant sustainable bio-oil quantities (UCO and Category 1 tallow) produced in England from competent uses or securing sufficient quantities of feedstock through imports.

4.1 The scale of the opportunity

England has a high proportion of users who are off the gas grid, with around 15% of households (about 3.3 million residential properties) not connected to the gas network [4]. Therefore, the development of domestic BioLPG production has an important role to play to meet its decarbonisation targets.

The total number of English properties that are currently using heating oil, LPG, and solid mineral fuels as their primary heating source is estimated to be about 1.1 million (figure 8) and, in a sense, define the scale of the opportunity for potential BioLPG suppliers in the domestic sector, as the vast majority of these properties are located in rural areas where an electrical solution is not always cost-effective.

A recent study conducted on behalf of the UK government [30] revealed that around 10% of the 1.3 million rural off gas grid dwellings in England and Wales are currently not suitable for an electric heating solution even if improvements to the low voltage network were made. These results are only based on the technical feasibility of different electric heating approaches, and do not consider the economic viability of these options. As a result, any policy developments should also consider the cost-effectiveness of electric heating approaches against low carbon heat alternatives.

Households that are already using LPG as heating fuel (around 147,000 in England) are the most obvious target market for BioLPG suppliers, as bio-propane is 100% compatible with their existing heating systems. Heating systems currently using fossil heating oil will need to be replaced or retrofitted in order to accommodate LPG or BioLPG. However, given the high capital cost of boilers/conversion kits, it is more likely that these households will wait for the end of the life of their existing oil heating systems, before considering any new low carbon heating option.

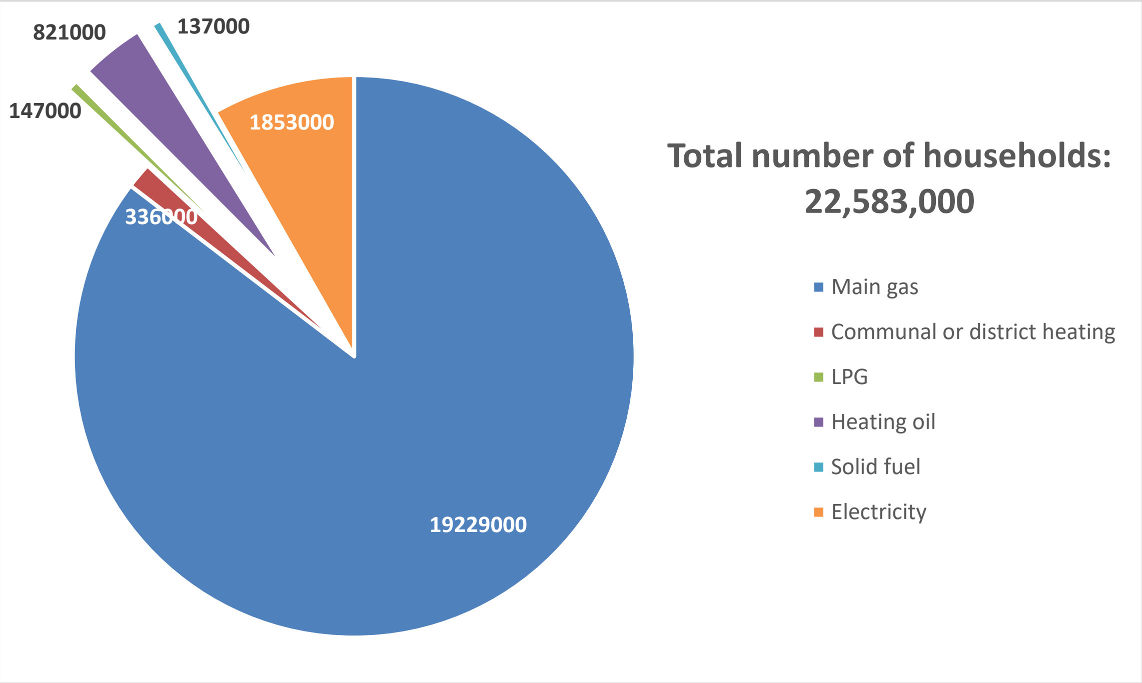


Figure 8: Primary heating fuel for households in England [4]

With regard to the non-domestic building stock, there are around 62,000 buildings heated with oil or LPG in England and Wales [3], with the industrial, storage, retail, and hospitality being the sectors with the largest number of premises using heating oil as primary fuel. These premises can theoretically form the target market for BioLPG suppliers in the English non-domestic heating sector.

In the transport sector, the UK government is planning to phase out petrol and diesel cars by 2032 [31], and meeting this target requires a rapid electrification of the domestic fleet. Still, there will be a substantial demand for sustainable liquid and gaseous fuels beyond 2032, both for old diesel/petrol cars and larger vehicles where todays batteries face limitations. Therefore, BioLPG offers a decarbonisation solution for existing LPG vehicles as well as for the future freight sector.

In addition, The Clean Air Zone Framework in England guides and facilitates the establishment of Clean Air Zones (CAZs) by Local Authorities [32]. Although there is no specific legal requirement for their introduction, a CAZ has already been introduced in London, while there is also activity for introducing CAZs in other cities, like Birmingham, Manchester, Leeds, and Oxford [33].

Any such interventions could increase the market for LPG vehicles, as they can substantially reduce PM and NOx emissions compared to diesel and petrol cars; LPG has been identified as having the potential to reduce pollutant emissions and as such could be considered for evaluation by local authorities as part of their Clean Air Zone planning [32].

4.2 Domestically available feedstock for the production of BioLPG

Bio-oils

The only process for the production of biopropane that is currently operating at the commercial scale is the hydrogenation or hydrotreating of vegetable oils, fats, and biomass-derived oils. One factor that can determine the potential of this technology to be implemented in England is securing adequate bio-oil quantities. Pure vegetable oils are not expected to be part of the feedstock mix, given the continuous reduction of the crop cap (table 2)[9].

According to E4tech, it is estimated that around 190,000 tonnes of used cooking oil (UCO) will be domestically generated in the UK during 2020 [34], most of which is expected to be collected in England, and utilized for other bioenergy purposes, mainly due to the existence of a number of biodiesel plants, such as the ones operated by Greenergy in Teesside and Immingham.

Based on our communications with FABRA, the trade association responsible for most rendering plants in the UK, around 350,000 tonnes of tallow have been produced in the UK by their members, giving an overview of the total availability. England seems to be responsible for the production of most of these volumes, considering the location of rendering plants in the UK (Appendix 7). However,

[9] The cap is expected to be filled mostly by crop-derived ethanol, which is typically produced from feedstocks with lower risk of causing indirect land use change compared to crop-derived biodiesel. It should be noted that a consultation was also published on 4 March 2020, setting out UK government proposals for introducing E10 Petrol, and at the time of writing, the UK government analyses the feedback received. RTFO targets are expected to increase by around 1.5% to account for this supply and ensure E10 will deliver additional carbon savings. Even with an increase in the overall targets, an increasing share of the bioethanol needs to come from waste/residues, considering that the crop cap will gradually decrease to 2% by 2032 [89].

the opportunity may be limited to Category 1 tallow[10], which can only be used for energy generation and its production potential is expected to be about half of the overall tallow quantities produced. At the current time, the majority of category 1 tallow produced in the UK seems to either be processed by Argent Energy, who is a UK based biodiesel producer, or by the rendering industry itself as a process fuel [35].

Residual waste

Gasification-based pathways appear to be a route with a potential to supply high volumes of bioLPG in the English market, using domestically available feedstock. Important volumes of residual mixed waste streams, which are common feedstock for syngas production, appear to be readily available for use in England. More specifically, around 2.8 million tonnes of untreated residual waste (mixed municipal waste) were destined to landfill during 2018-2019 [36], corresponding a significant reduction compared to 2010 levels as shown in figure 9. In addition, 2.71 million tonnes of RDF/SRF were exported from England in 2019, down from 3.13 million tonnes in 2018 and 3.46 million tonnes in 2017 [37]. as the gap between treatment capacity and arisings closes[11].

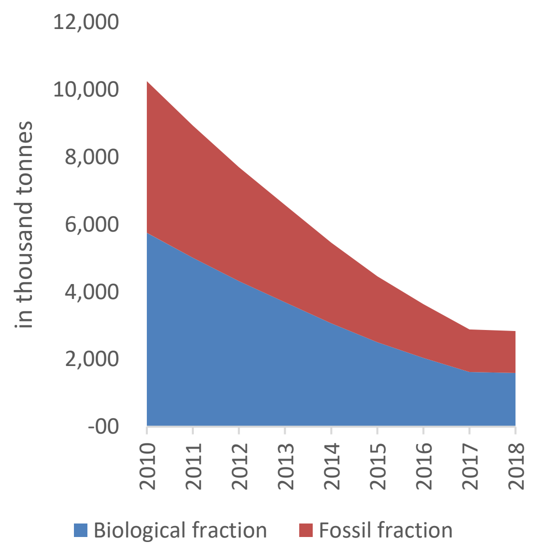


Figure 9: Untreated mixed MSW destined to landfill between 2010 and 2018 in England [38]

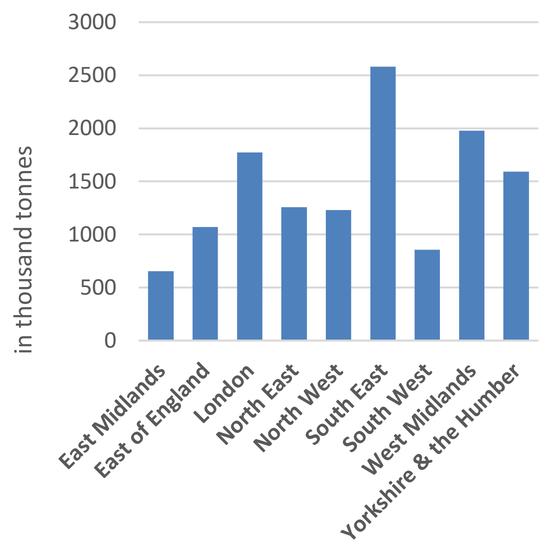


Figure 10: Volumes of MSW incinerated in different regions in 2017 [39]

Although this trend is expected to continue and the total residual waste arisings are projected to fall significantly - based on the Resources and Waste Strategy (RWS) [40], England aims to increase the MSW recycling rate to 65% and reduce the municipal waste to landfill to 10% or less by 2035- UK policies are also encouraging the diversion of residual waste away from landfill and towards higher-

[10] Legally permissible end uses for category 1 tallow are, at present, generally limited to energy generation. On the other hand, Category 2 and 3 tallow is allowed to be used in higher value markets (category 2 can be used in industrial applications, while category 3 in soaps and cosmetics.

[11] Only the biological fraction of these waste streams (e.g. paper waste) can contribute to the production of BioLPG, as the rest consists of fossil resources (e.g. plastics), and the end fuel can be classified as a low-carbon fossil LPG.

value uses, such as the production of advanced biofuels. Therefore, certain quantities of residual waste that are currently handled in energy-from-waste facilities can potentially be used for the production of BioLPG. Figure 10 presents the volumes of MSW that are incinerated in different regions in England in 2017. It is expected that 'energy from waste' plants are going to close over time, unlocking residual waste contracts for the production of BioLPG in the longer term.

Woody biomass

Sustainable woody biomass is another feedstock type that is typically used for the production of syngas by gasification. Figure 11 presents estimated volumes of forestry residues[12] generated in England across different regions and can be used for the production of wood pellets and briquettes for use in the production of BioLPG.

Significantly higher volumes of waste wood, about 3.9 million tonnes, appear to be produced in England across different regions as shown in figure 11[13]. Although, data on regional availability of waste wood is quite old (2009), volumes presented are expected to be relevant in today terms, while annual production is projected to remain constant by 2030 [41].

It should be noted that of the volumes presented in figure 11, only the wood waste streams that may be contaminated (e.g. painted, coated, or laminated wood) can be used for bioenergy, and their contribution to the overall figures is unclear. This is because the use of non-contaminated waste wood for the production of biofuels does not respect the waste hierarchy, as the opportunities for recycling are considerably higher.

Considering the feedstock volumes used for the production of wood pellet in the UK between 2013-2017 (figure 12), as well as the quantities of waste wood currently recycled in the UK, around 2.8 million tonnes [42], it is not clear whether there are adequate quantities currently available to justify the development of a BioLPG plant. A more detailed regional analysis is recommended to identify whether there is significant potential.

[12] Forestry residues refer to bark, tops and branches left from the harvesting operation, and in some cases tree stumps that are normally left in the forest after felling.
[13] Volumes presented refer to wood waste arisings from the packaging, industrial, construction, demolition, and municipal sectors and to the best of our understanding include sawmill residues.

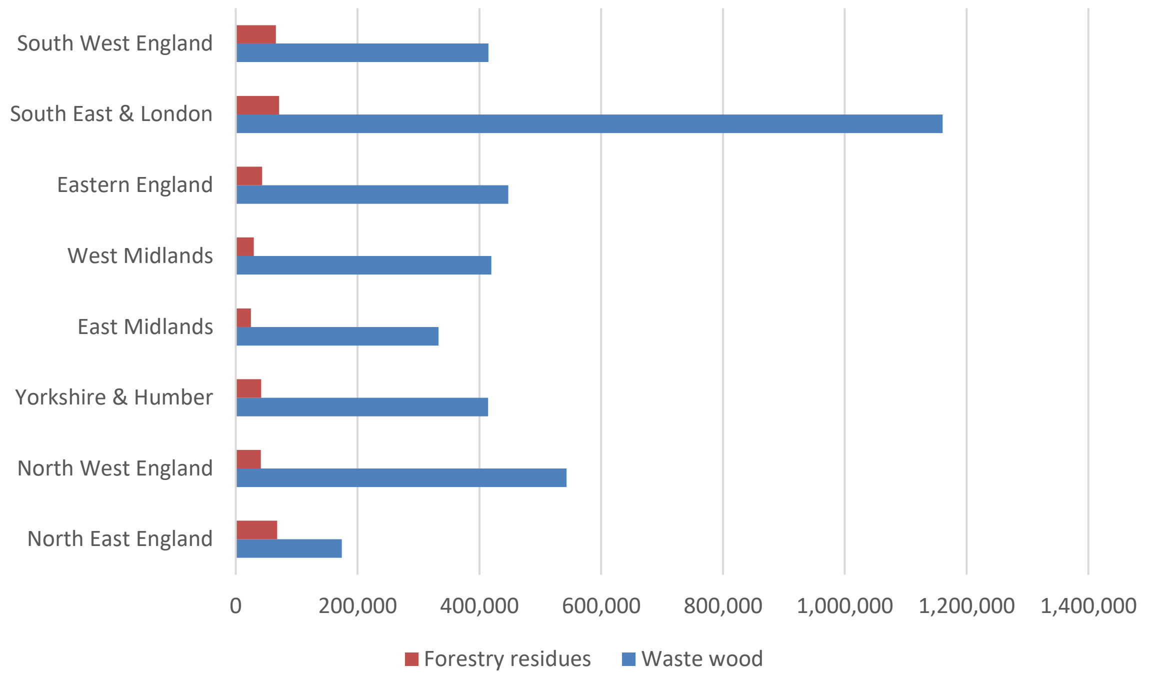
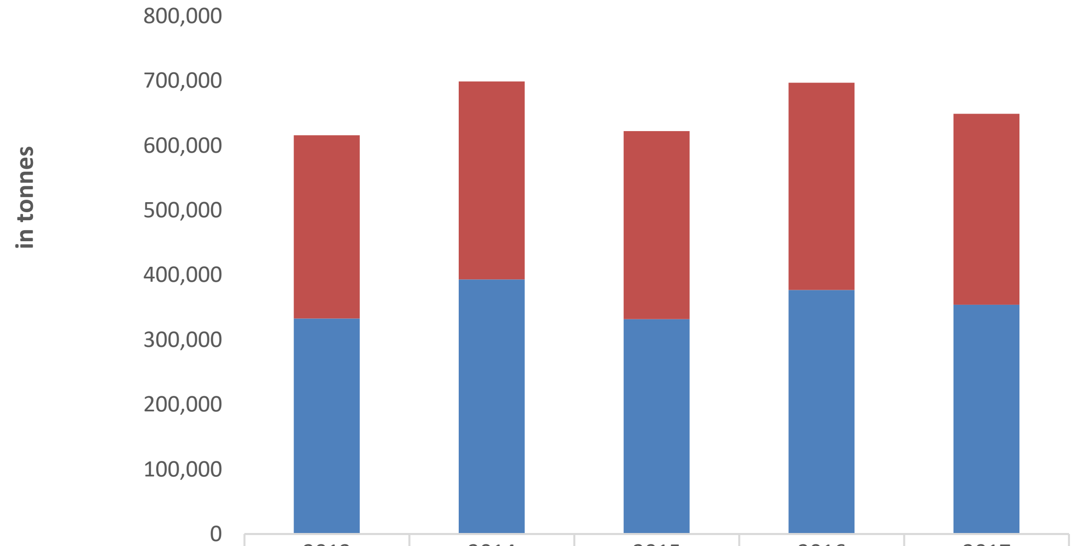


Figure 11: Estimated regional volumes of forestry residues and waste wood arisings in England (before competing uses) [43], [44]



	2013	2014	2015	2016	2017
Sawmill products	283,000	306,000	290,000	320,000	295,000
Low grade roundwood	333,000	393,000	332,000	377,000	354,000

Low grade roundwood   Sawmill products

Figure 12: Feedstock used for the production of wood pellet in the UK, 2013-2017 [45]

Note: Sawmill products may also include wood from other sources (e.g. energy crops, arboriculture arisings and waste wood).

Sugars

England appears to be an attractive location for the production of isobutene, as the only Nation in the United Kingdom with an active sugar refining industry. The technology developer, Global Bioenegies, seems to actively be looking for industrial symbiosis opportunities with existing sugar refiners, as they have already formed a Joint Venture with Crystal Union for commissioning a commercial facility in 2022 outside the UK.

Sugar beet harvesting equipment and suitable land, on rotation, are available (sugar beet requires certain soils), while there are also opportunities for expansion with the right offer from sugar biorefineries. Isobutene produced from first generation sugars is not subject to any crop-cap, provided that it will be used exclusively in residential, commercial, and process heating markets.

Opportunities also exist for the production of second-generation isobutene, utilising agricultural residues (mainly straw), provided that lignocellulosic feedstock pre-treatment technologies will be cost-effectively deployed at a commercial scale. As shown in figure 13, a high straw surplus - the resource available after competing uses (predominately as a bedding material which is a high value market) - is expected to be available in England, that is typically chopped and returned to land. In case of further exploitation, the value of straw to land in terms of organic matter and soil nutrients should be considered. Sustainable removal rates appear to range between 30 to 60% [46], and beyond this point, straw possibly need to be replaced with other organic fertilisers, such as compost.

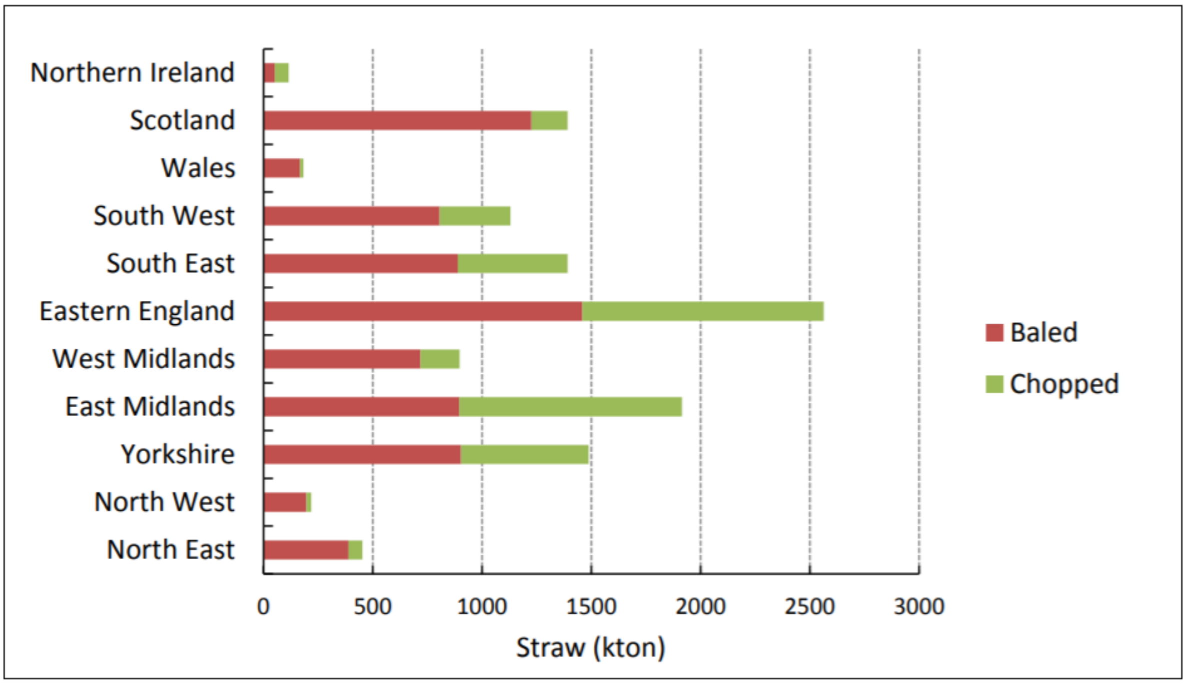


Figure 13: Regional comparison of straw available from all cereal crops [43]

4.3 BioLPG production potential and strategic plant locations

Gasification based pathways appear to have the highest potential for producing significant volumes of BioLPG in England, mostly through the valorisation of residual waste (unprocessed mixed municipal solid waste) currently destined to landfills and RDF quantities exported (around 2.71 million tonnes in 2019). These RDF quantities, on their own, could lead to the production of about 300,000 tonnes of a mixture of bio-LPG and fossil LPG (low carbon fossil fuel)[14], which equates to about 30% of the current LPG demand in the United Kingdom.

E4tech identified 2 strategic locations for plants valorising residual waste for the production of advanced biofuels (Appendix 8), with the main selection criteria being the quantities of MSW currently going to landfill or incinerated without energy recovery in different regions as well as access to ports for potential import of feedstock or diversion of currently exported RDF [41]. Those areas should be seen as promising locations, where detailed feedstock due diligence studies need to be carried out before any investment decisions.

Fermentation of sugars to isobutene is another pathway with potential to support BioLPG production, but one should bear in mind that it is not clear whether the fuel output is 100% compatible with existing LPG infrastructure. Therefore, the degree to which this technology can be deployed in the English heating market is subject to whether there is a blend limit. Easter England is an attractive location for building a biorefinery, as all four UK sugar beet processing facilities are located there and operated by British sugar.

The reported energy conversion yields are high, around 87% [47], and therefore feedstock availability is not expected to be a limiting factor for the development of a facility with production capacity of 50,000 tonnes or higher, that would be sufficient for covering a significant part of the total LPG demand in England.

Second generation biorefineries could also provide additional isobutene quantities with Eastern England, East Midlands, and Yorkshire being the most suitable regions, mainly due to the high straw availability in those regions, but the overall process is by far more complicated, and its technical and economic feasibility requires investigation.

It is important to note that hydrogenation of triglycerides is the only technology that is currently commercially available and can supply certain BioLPG volumes in the short term, but this requires either the diversification of significant sustainable bio-oil quantities (UCO and Category 1 tallow) produced in England from competent uses, such as FAME production, or securing sufficient quantities of feedstock through imports.

Opportunities exist in utilizing established oil refining capacity. The 4 refineries located in England, illustrated in Appendix 9, can co-process very large volumes of bio-oils with petroleum intermediates, without reaching any blending limits. This option is particularly attractive because oil refinery already produces fossil LPG and are connected to the LPG distribution network. Still, the overall potential is

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[14] RDF is a partially renewable feedstock; the exact bio-based quantities depend on the energy value of the bio-based component of residual waste compared to the fossil one and are expected to be around 50-50.

expected to be limited, as BioLPG is produced only as a by-product of the HVO diesel production. Indicatively, meeting 5% of the overall UK demand would require the procurement of about 1.5 million tonnes of sustainable bio-oils, a requirement 3 times higher than the current UCO and tallow arisings in the UK.

5 BioLPG production opportunities in Scotland

Key findings

- In its energy strategy, the Scottish government acknowledges that gaseous fuels will remain an important part of Scotland's energy mix for the foreseeable future, while they also recognise that LPG has an important role to play, especially when derived from bio-based sources.
- Scotland has a high proportion of users who are off the gas grid, with around 400,000 residential properties not connected to the gas network in 2018, with two-thirds of those homes being located in rural areas.
    - Households that are already using LPG as heating fuel (around 25,000) are the most obvious target market for BioLPG suppliers, as bio-propane is 100% compatible with their existing heating systems.
- With regard to non-domestic building stock, the Scottish government estimates that more than 100,000 non-domestic buildings do not currently use main gas for heat.
    - Even though the majority of these buildings are electrically heated, still there is a significant number of premises that use fossil LPG and heating oil fuels as their primary heat source and are probably not suitable for an electrical solution.
- In the transport sector, the Scottish Government is committed to introduce Low Emission Zones (LEZs) into Scotland's four biggest cities between 2018 and 2020, and then into all other Air Quality Management Areas by 2023 where the National Low Emission Framework (NLEF) appraisals show this is the correct mitigation.
    - Indeed, Glasgow is the location of Scotland's first low emission zone, introduced at the end of 2018, while Edinburgh, Dundee, and Aberdeen are expected to implement low emission zones during 2020.
    - This intervention may increase the market for LPG vehicles in Scotland, as they can substantially reduce PM and NOx emissions compared to diesel and petrol cars.
- Gasification-based pathways appear to be the only known route with the capabilities to result in a 100% BioLPG transition in Scotland using nationally available resources.
    - This is the result of the relatively high volumes of available domestic sustainable woody biomass and the relatively high BioLPG energy conversion yields.
    - RDF volumes currently available in Scotland are also significant and can potentially support indigenous production.
- Opportunities also exist in utilizing existing capacity of the Grangemouth Refinery, which is the only refinery in Scotland with a refining capacity of around 28,000 tonnes per day.
    - This available capacity suggests that very large volumes of bio-oils can be co-processed with petroleum intermediates, without reaching any blending limits.

5.1 The scale of the opportunity

Following CCC's recommendations, Scotland has its own decarbonisation targets that reflect the fact that it is the Devolved Administration with the greatest potential to remove emissions. The Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 has set new targets for Scotland to reduce all greenhouse gases to net zero by 2045 at the latest, with interim targets for reductions of at least 56% by 2020, 75% by 2030, 90% by 2040 [48].

In its energy strategy [49], the Scottish government acknowledges that gaseous fuels will remain an important part of Scotland's energy mix for the foreseeable future and meeting this demand with a lower carbon secure energy system will be a key challenge, while they also recognise that LPG has an important role to play, especially when derived from bio-based sources. Scotland has a high proportion of users who are off the gas grid, with around 15.3% of households (nearly 400,000 residential properties) not connected to the gas network in 2018, with two-thirds of those homes being located in rural areas.

Table 3 presents the percentage of Scottish households that use each type of primary heating fuel between 2013 and 2017. The total number of properties that are currently using heating oil, LPG, and solid mineral fuels as their primary heating source is estimated to be about 196,000 and, in a sense, define the scale of the opportunity for potential BioLPG suppliers in the domestic sector, as the vast majority of these properties are expected to be located in rural areas where an electrical solution is not always cost-effective.

Table 3: Primary heating fuel for households in Scotland (2013 – 2017) [48]

Primary heating Fuel	2013	2014	2015	2016	2017
Mains gas	78%	78%	79%	79%	79%
Electricity	13%	13%	12%	11%	12%
Oil	6%	6%	7%	6%	6%
Communal heating	1%	1%	1%	1%	1%
LPG bulk or bottled	1%	1%	1%	1%	1%
Solid mineral fuel	1%	1%	1%	1%	1%
Biomass	0%	0%	1%	1%	1%
Other	0%	0%	0%	0%	0%

Households that are already using LPG as heating fuel (around 25,000) are the most obvious target market for BioLPG suppliers, as bio-propane is 100% compatible with their existing heating systems. Heating systems currently using fossil heating oil will need to be replaced in order to accommodate LPG or BioLPG. However, given the high capital cost of boilers/conversion kits, it is more likely that these households will wait for the end of the life of their existing oil heating systems, before considering any new low carbon heating option.

With regard to non-domestic building stock, which ranges from small shop and business units to large office buildings, industrial units, and shopping centres, the Scottish government estimates that more than 100,000 (58%) non-domestic buildings (excluding military and agricultural buildings) do not currently use main gas for heat (figure 14). Even though the majority of these buildings are electrically heated, still there is a significant number of premises that use fossil LPG and heating oil fuels as their primary heat source and are probably not suitable for an electrical solution. These premises can theoretically form the target market for BioLPG suppliers in the Scottish non-domestic heating sector.

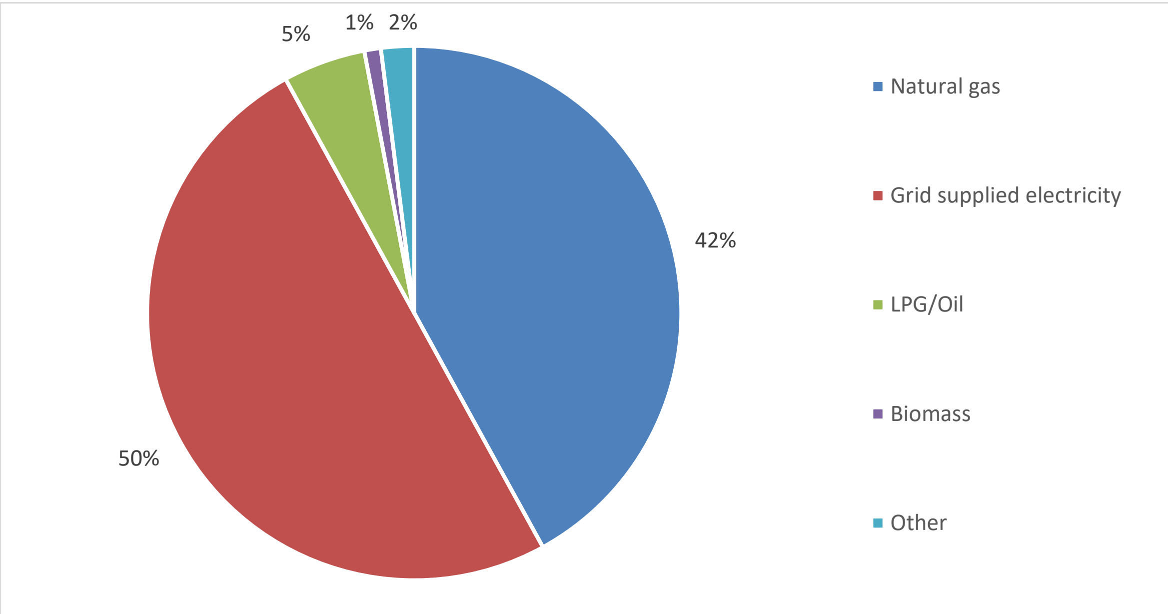


Figure 14: Primary heating fuel for non-domestic premises in Scotland (1/2013-7/2017) [48]

In the transport sector, Scotland is planning to phase out petrol and diesel cars by 2032, three years ahead of the rest of the UK, and meeting this target requires a rapid electrification of the domestic fleet. Still, there will be a substantial demand for sustainable liquid and gaseous fuels beyond 2032, both for old diesel/petrol cars and larger vehicles where todays batteries face limitations. Therefore, BioLPG offers a decarbonisation solution for existing LPG vehicles as well as for the future freight sector.

In addition, the Scottish Government is committed to introduce Low Emission Zones (LEZs) into Scotland's four biggest cities between 2018 and 2020, and then into all other Air Quality Management Areas by 2023 where the National Low Emission Framework (NLEF) appraisals show this is the correct mitigation. Indeed, Glasgow is the location of Scotland's first low emission zone, introduced at the end of 2018, while Edinburgh, Dundee, and Aberdeen are expected to implement low emission zones during 2020 [49]. This intervention may increase the market for LPG vehicles, as they can substantially reduce PM and NOx emissions compared to diesel and petrol cars.

5.2 Domestically available feedstock for the production of BioLPG

Bio-oils

At the current time, 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. One factor that can determine the potential of this technology to be implemented in Scotland is securing adequate bio-oil quantities. Pure vegetable oils are not expected to be part of the feedstock mix, given the continuous reduction of the crop cap (table 3)[15].

Sourcing of used cooking oils (UCO) may also be challenging, as most of the domestically collected quantities, 18,000 tonnes per annum (figure 16), are expected to be currently utilized for other bioenergy purposes, mainly due to the existence of the biodiesel plant at Motherwell in Scotland.

Higher quantities of tallow are expected to be available for producing HVO diesel and BioLPG, as based on Ricardo estimates, around 18,000 tonnes of tallow (category 1) produced in Scotland are not currently used for bioenergy purposes[16]. Still, nationally produced feedstock is not sufficient to justify production and the development of this technology in Scotland will be primarily dependant on imports.

Woody biomass

Considering any limits on the availability of sustainable bio-oils, gasification-based pathways appear to be the only known route to supply high volumes of BioLPG in the Scottish market. Indeed, relatively high volumes of domestic sustainable woody biomass and RDF, which are common feedstocks for syngas production, appear to be readily available for use in Scotland (figure 16). Figure 15 also shows that most of the UK's forestry industry is located in Scotland, and therefore it is expected to be the most attractive location for the development of a wood biorefinery.

[15] The cap is expected to be filled mostly by crop-derived ethanol, which is typically produced from feedstocks with lower risk of causing indirect land use change compared to crop-derived biodiesel. It should be noted that a consultation was also published on 4 March 2020, setting out UK government proposals for introducing E10 Petrol, and at the time of writing, the UK government analyses the feedback received. RTFO targets are expected to increase by around 1.5% to account for this supply and ensure E10 will deliver additional carbon savings. Even with an increase in the overall targets, an increasing share of the bioethanol needs to come from waste/residues, considering that the crop cap will gradually decrease to 2% by 2032 [89].

[16] Legally permissible end uses for category 1 tallow are, at present, generally limited to energy generation. On the other hand, Category 2 and 3 tallow is allowed to be used in higher value markets (category 2 can be used in industrial applications, while category 3 in soaps and cosmetics.

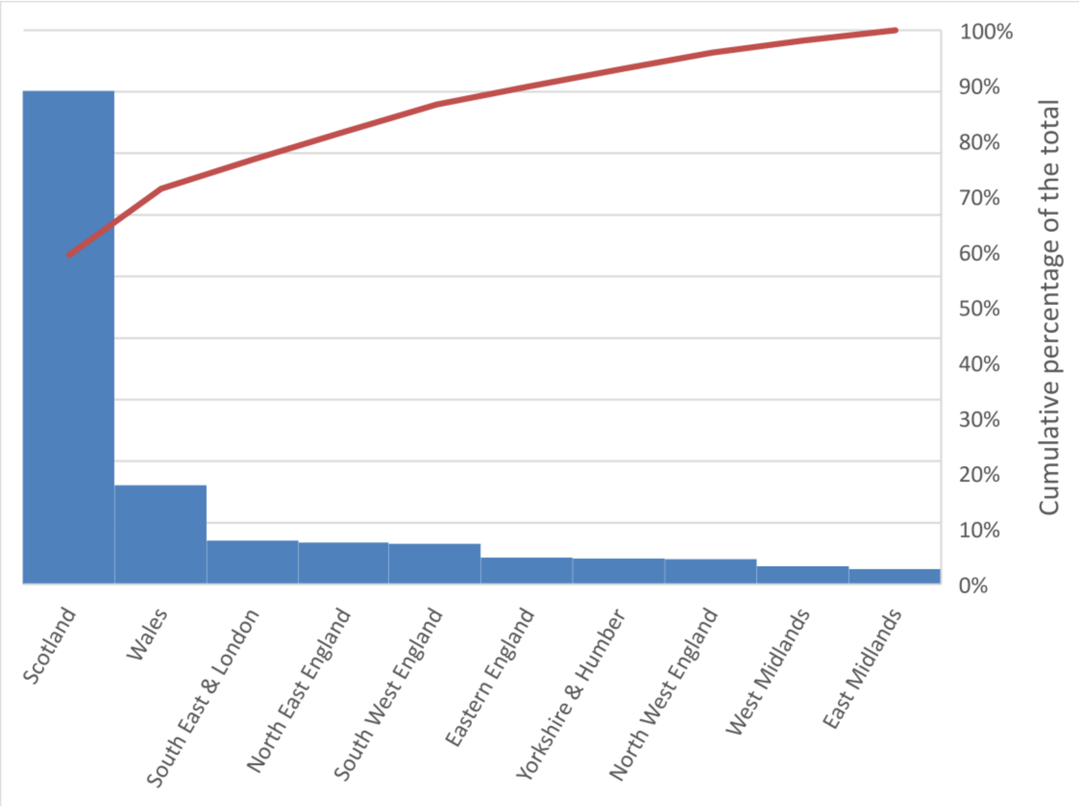


Figure 15: Sustainable and recoverable dry tonnes of forest waste arisings in GB [43]

Residual waste

RDF is another feedstock type that is typically used for the production of syngas by gasification, but it is a partially renewable feedstock, meaning that only its biogenic fraction can contribute to BioLPG production. Based on data provided in figure 16, the volumes of the RDF (biogenic fraction) currently available in Scotland are significant and can potentially support an indigenous BioLPG production.

Sugars

At the current time, Scotland is not an ideal location for the development of an isobutene production biorefinery due to the absence of sugar industry in the area, as the developer (Global Bioenergies) seems to prioritise industrial symbiosis opportunities with existing sugar refineries and the utilisation of sucrose from sugar beet[17]. Still, opportunities may exist in utilising starch-containing biomass for the production of glucose and subsequently isobutene, using cereal produced in Scotland, but any land-use trade-offs and the competitiveness of cereal production yields for fuel production need to be carefully be examined.

[17] As a side note, a sugar beet processing plant was located in Scotland, but yields are expected to be lower and any land use trade-offs need to be carefully examined. low yields and the seasonality of supply led the plant to close in the 1970's. There are some proposals for re-establishing sugar beet production and processing in Scotland, following a feasibility study conducted by NNFCC on behalf of Scottish Enterprise [90], but it is not clear whether these plans will become a reality.

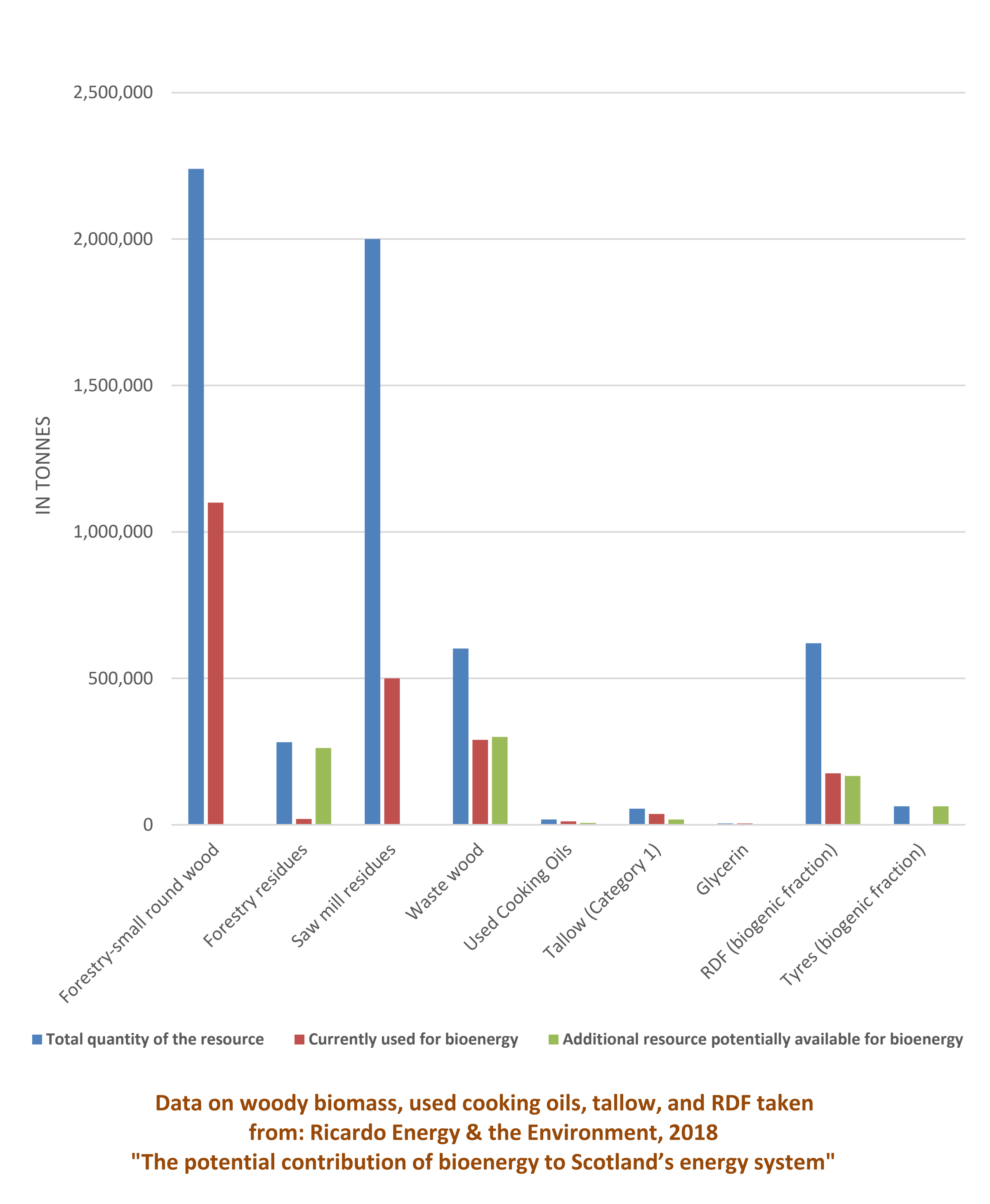


Figure 16: Domestic feedstock available for BioLPG production in Scotland [50]

5.3 BioLPG production potential and strategic plant locations

Gasification based pathways appear to have the highest potential for producing significant volumes of BioLPG in Scotland, mostly using sustainable woody biomass as feedstock. More specifically, figure 17 gives estimates on the BioLPG production potential of different technologies using domestically available feedstock in Scotland, currently available for bioenergy, and presented against likely LPG demand in Scotland to provide an indication of their significance.

It is clear that gasification-based pathways appear to be the only known route with the capabilities to result in a 100% BioLPG transition using nationally available resources. This is the result of the relatively high volumes of available domestic sustainable woody biomass (mostly forestry residues), and the relatively high BioLPG energy conversion yields (around 50-60% [51]).

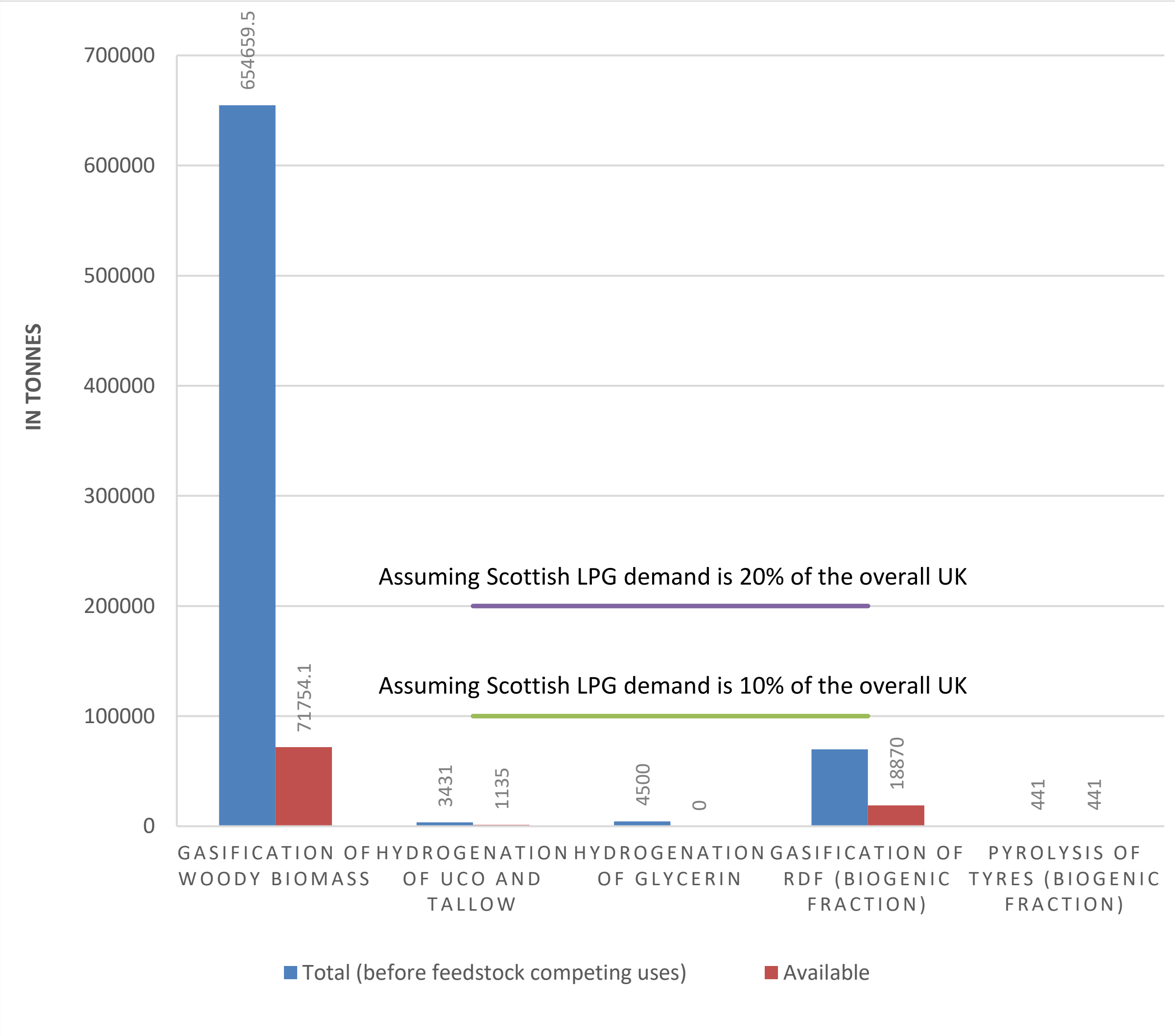


Figure 17: Estimated BioLPG production potential using domestically available feedstock in Scotland[18]

[18] LPG demand in Scotland is not publicly available, but the two major LPG suppliers in Scotland (Flogas and Calor), which are expected to be the main interested parties, will be able to provide some relevant information.

E4tech identified 3 potential plant locations for biorefineries valorising forest residues (Appendix 10) [41]. The location selection was based mainly on the potential availability of local feedstock, known competing demands, and the suitable local transport links already serving the area. Identified locations refer to a general area rather than a specific location, the potential of which should be further examined through detailed feasibility studies.

RDF can also support production, considering that it is a partially renewable feedstock and together with the BioLPG volumes presented in figure 17, similar volumes of fossil LPG, that can be classified as low fossil fuel, will also be produced.

It is important to note that hydrogenation of triglycerides is the only technology that is currently commercially available and can supply certain BioLPG volumes in the short term, but sustainable waste bio-oil quantities domestically available are not enough to justify the development of a dedicated standalone plant, and any production efforts should be based on imports.

Opportunities exist in utilizing existing capacity of the Grangemouth Refinery (Appendix 9), which is the only refinery in Scotland with a refining capacity of 210,000 barrels (around 28,000 tonnes) per day [52]. This available capacity suggests that very large volumes of bio-oils can be co-processed with petroleum intermediates, without reaching any blending limits. This option is particularly attractive because existing hydrotreaters are already connected to the LPG distribution network while refineries have high flexibility to change feedstocks in response to supply shortages.

There is an additional aspect on this as, unlike dedicated HVO units, oil refineries can also process pyrolysis oil that can yield certain quantities of BioLPG. This increases the diversity of feedstocks available to producers, adding flexibility to secure bio-oils from a range of highly available non-food crop feedstocks in Scotland, such as waste tyres (figure 16). Pyrolysis technologies can either be deployed in the proximity of the oil refinery or on a decentralised basis at smaller scale, near woody biomass resources for example. However, bioLPG production potential of pyrolysis oil is relatively low, and bioLPG should not be the focus of these efforts.

6 BioLPG production opportunities in Wales

Key findings

- BioLPG has an important role to play for Wales to meet its decarbonisation targets. Wales has a high proportion of users who are off the gas grid, with around 21% of households not connected to the gas network.
- Data show that there is a significant number of non-domestic premises that use fossil LPG, heating oil, and solid fuels as their primary heat source and are probably not suitable for an electrical solution.
- Wales' domestic and non-domestic buildings include some of the oldest, traditionally constructed buildings in Europe, with a high number of solid walls and hard to treat off-gas properties, fact that makes their electrification more difficult and expensive.
- The "Clean Air Zone Framework for Wales" guides and facilitates the establishment of Clean Air Zones (CAZs) by Local Authorities.
  - LPG vehicles are considered to meet the requirements of a CAZ under this Framework.
  - Cardiff has been identified by DEFRA as an area that may need to introduce a CAZ to achieve urgently needed compliance with air quality limit values stipulated in legislation.
  - Cardiff already has 2 LPG refuelling stations, which can be rapidly expanded at no cost to the taxpayer.
- Opportunities for valorising domestically available feedstock, for the production of BioLPG, seem to be limited to around 150,000 tonnes of untreated residual waste that are currently destined to landfill as well as to the 50,000 tonnes of RDF that are exported to countries outside the UK.
  - Additional residual waste volumes that are currently destined to 'energy from waste' might be available for longer term production, but this is subject to existing contracts.
  - Mid & South West Wales seems to be the most attractive location for developing a residual waste processing facility.
- Opportunities also exist in utilizing existing capacity of the Pembroke Refinery, which is the only refinery in Wales with a refining capacity of around 36,000 tonnes per day, including 220,000 barrels of crude oil and 50,000 of other feedstock, possibly referring to biooils.
  - This available capacity suggests that very large volumes of bio-oils can be co-processed with petroleum intermediates, without reaching any blending limits.
  - Exploiting this opportunity requires securing sufficient quantities of feedstock through imports.
- Alternatively, a 100% BioLPG transition in Wales can also achieved by importing roughly 300,000-1,000,000 tonnes of woody biomass, depending on size of the LPG market.

6.1 The scale of the opportunity

Wales has its own decarbonisation targets that reflect the fact that it has a more difficult path to reach net zero by 2050, compared to the other Devolved Administrations, partly because of its high agricultural emissions. Following CCC recommendations, the Welsh government aims for a 95% reduction by 2050, with an ambition to reach net-zero [53].

BioLPG has an important role to play for Wales to meet its decarbonisation targets. Wales has a high proportion of users who are off the gas grid, with around 21% of households (about 294,000 residential properties) not connected to the gas network [54]. In addition, Wales' domestic and non-domestic buildings include some of the oldest, traditionally constructed buildings in Europe, with a high number of solid walls and hard to treat off-gas properties[19].

The total number of properties that are currently using heating oil, LPG, and solid mineral fuels as their primary heating source in Wales (figure 18) define the scale of the opportunity for BioLPG suppliers in the domestic sector. The vast majority of these properties are located in rural areas, where an electrical solution is not always cost-effective.

Households that are already using LPG as heating fuel (around 25,000 in Wales) are the most obvious target market for BioLPG suppliers, as bio-propane is 100% compatible with their existing heating systems. Heating systems currently using fossil heating oil will need to be replaced in order to accommodate LPG or BioLPG. However, given the high capital cost of boilers/conversion kits, it is more likely that these households will wait for the end of the life of their existing oil heating systems, before considering any new low carbon heating option.

With regard to non-domestic building stock, which ranges from small shops and business units to large office buildings, hospitals, and shopping centres, data show that there is a significant number of premises that use fossil LPG, heating oil, and solid fuels as their primary heat source and are probably not suitable for an electrical solution [55]. As with the domestic sector, much of the 2050 built environment, will not have been designed or constructed with energy efficiency and decarbonisation standards in mind, and these premises can theoretically form the target market for BioLPG suppliers.

[19] It should be noted that new construction offers opportunities to incorporate new energy systems; and to implement much higher standards of energy efficiency. However, based on Welsh government estimates, around 65-70 per cent of the dwelling stock in existence in the 2050s is likely to have been built before 2000 [91].

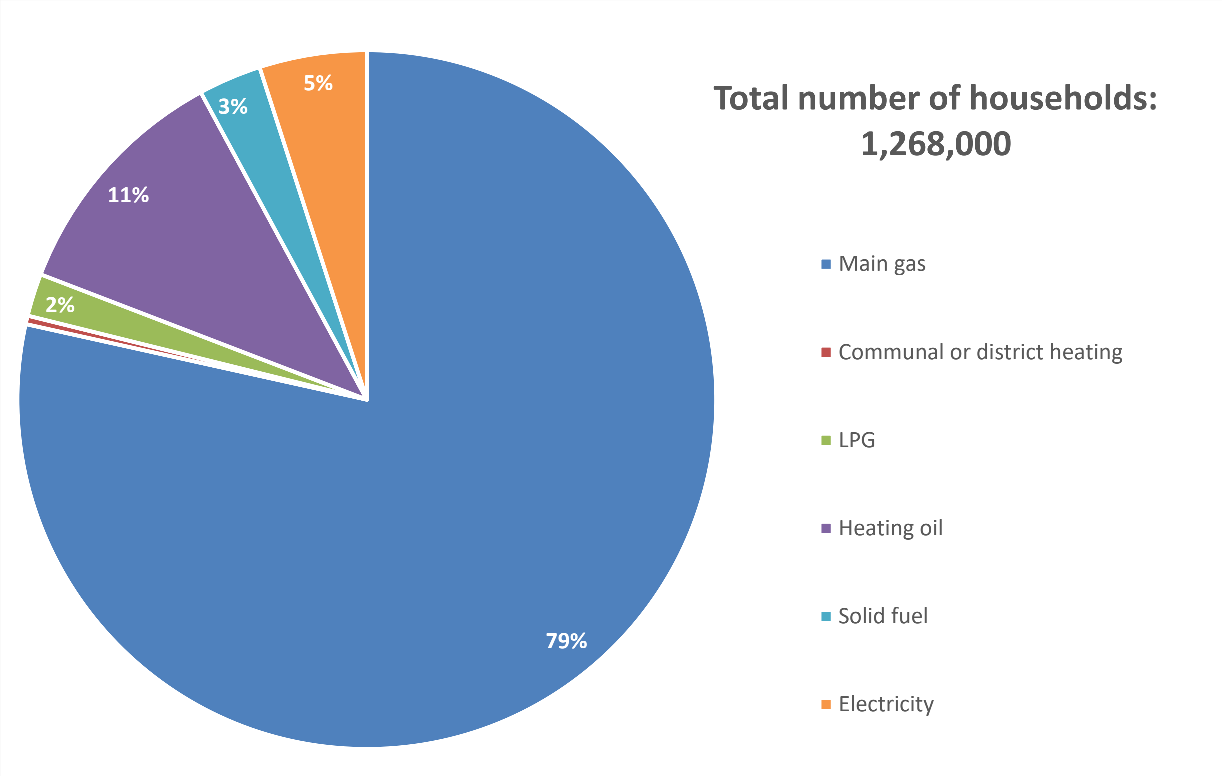


Figure 18: Primary heating fuel for households in Wales [4]

In the transport sector, the UK government is planning to phase out petrol and diesel cars by 2035 [31], and meeting this target requires a rapid electrification of the domestic fleet. Still, there will be a substantial demand for sustainable liquid and gaseous fuels beyond 2032, both for old diesel/petrol cars and larger vehicles where todays batteries face limitations. Therefore, BioLPG offers a decarbonisation solution for existing LPG vehicles as well as for the future freight sector; the latter is significant as light/heavy trucks and buses are responsible for 4.2% of the total Welsh emissions [56].

In addition, The Clean Air Zone Framework for Wales guides and facilitates the establishment of Clean Air Zones (CAZs) by Local Authorities. Although there is no specific legal requirement to introduce a CAZ, modelling undertaken by Department for Environment, Food and Rural Affairs (DEFRA) has identified areas across the UK, including Cardiff, that may need to introduce a CAZ to achieve urgently needed compliance with air quality limit values stipulated in legislation [57].

Any such intervention in the Cardiff area, could increase the market for LPG vehicles, as they can substantially reduce PM and NOx emissions compared to diesel and petrol cars; LPG powered vehicles are considered to meet the requirements of a CAZ under this Framework without any further modifications. Cardiff already has 2 LPG refuelling stations, at the time of writing, which can be rapidly expanded at no cost to the taxpayer [58].

6.2 Opportunities to valorise domestically available feedstock

6.2.1 Bio-oils

Based on our estimates, about 15,000 tonnes of UCO are domestically generated in Wales every year, the majority of which is expected to be currently collected and sold abroad due to the absence of local biodiesel production. Certain quantities of tallow are also generated in Wales, due to the presence of a rendering plant in the Southwestern part of the country [59] (Appendix 7), and can potentially be used for the production of HVO diesel and BioLPG. However, at the current time the majority of category 1 tallow[20] produced in the UK seems to either be used by Argent Energy, who is a UK based biodiesel producer, or by the rendering industry itself as a process fuel [35].

6.2.2 Residual waste

Gasification-based pathways appear to be a route with a potential to supply high volumes of BioLPG in the Wales market, using domestically available feedstock. Important volumes of residual mixed waste streams, which are common feedstock for syngas production, appear to be readily available for use in Wales. More specifically, as shown in figure 19, around 155,000 tonnes of residual waste (untreated mixed municipal waste) were destined to landfill during 2018-2019, while around 50,000 tonnes of RDF were also exported the same period to countries outside the UK [60][21].

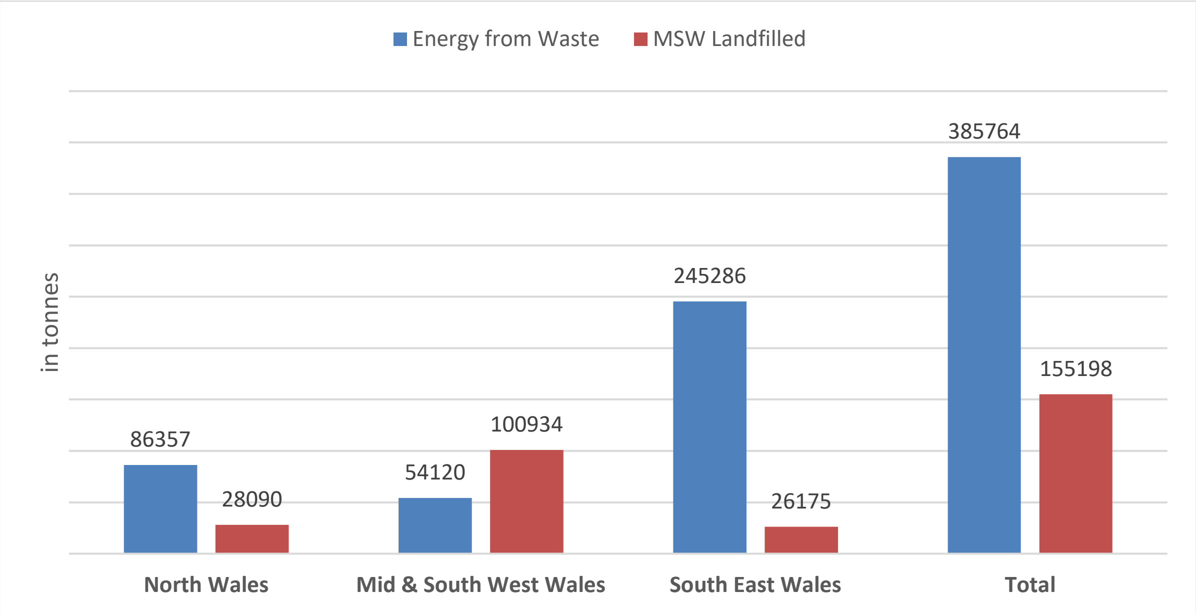


Figure 19: MSW landfilled and incinerated (with energy recovery) in Wales in 2018-2019 [61]

[20] Legally permissible end uses for category 1 tallow are, at present, generally limited to energy generation. On the other hand, Category 2 and 3 tallow is allowed to be used in higher value markets (category 2 can be used in industrial applications, while category 3 in soaps and cosmetics.

[21] Only the biological fraction of these waste streams (e.g. paper waste) can contribute to the production of BioLPG, as the rest consists of fossil resources (e.g. plastics), and the end fuel can be classified as a low-carbon fossil LPG.

Although the total residual waste arisings are projected to fall significantly by 2030, due to the increasing reuse and recycling targets[22], UK policies are also encouraging the diversion of residual waste away from landfill and towards higher value uses, such as the production of advanced biofuels. Therefore, residual waste that are currently handled in energy-from-waste facilities can potentially be used for the production of BioLPG.

The only 'energy from waste' project currently in operation in Wales is the 30 MW Trident Park energy recovery facility in Cardiff, which has been commissioned in 2015 and has the capacity to treat around 350,000 tonnes of municipal waste per annum [62]. Considering the 25-year lifetime of this facility, additional residual waste quantities for the production of BioLPG or other advanced biofuels will only be unlocked in 2040.

Nevertheless, 'Towards Zero Waste', the overarching waste strategy document for Wales, sets out a target for limiting the maximum level of municipal waste to be treated in energy-from-waste facilities to 30% by 2025 [63]. Still, it is not clear whether a longer-term BioLPG production from residual waste is in line with the intentions of the Welsh waste management policy, as its ultimate aim is achieving 100% recycling by 2050, and therefore no residual waste available for recovery.

6.2.3 Woody biomass

Woody biomass is another feedstock type that is typically used for the production of syngas. Figure 20 presents woody biomass quantities generated in Wales and can potentially be used for the production of BioLPG.

Contaminated wood refers to quantities that may be contaminated with heavy metals or halogenated compounds, a fact that makes their recycling challenging and advanced biofuel production a promising alternative. However, the use of non-contaminated waste wood for the production of biofuels does not respect the waste hierarchy, as the opportunities for recycling are considerably higher.

The clean wood fuel volume refers to roundwood, brash, sawmill residues, and arboricultural arisings, but their contribution to the total value is unclear. It is expected that most of these volumes can be used in the production of BioLPG with no restrictions.

Biomass heat projects represent over two-thirds of all renewable heat capacity in Wales, with a total thermal capacity of 443 MW from 3,345 projects [64], and therefore, it is expected that a significant part of the woody biomass arisings is already utilized.

[22] Wales achieved a 62.8% recycling during 2018/2019 of local authority municipal waste (including both household and non-household waste), while the 'Towards Zero Waste' strategy sets out a target for achieving recycling rates of 70 per cent by 2024/25 [92].

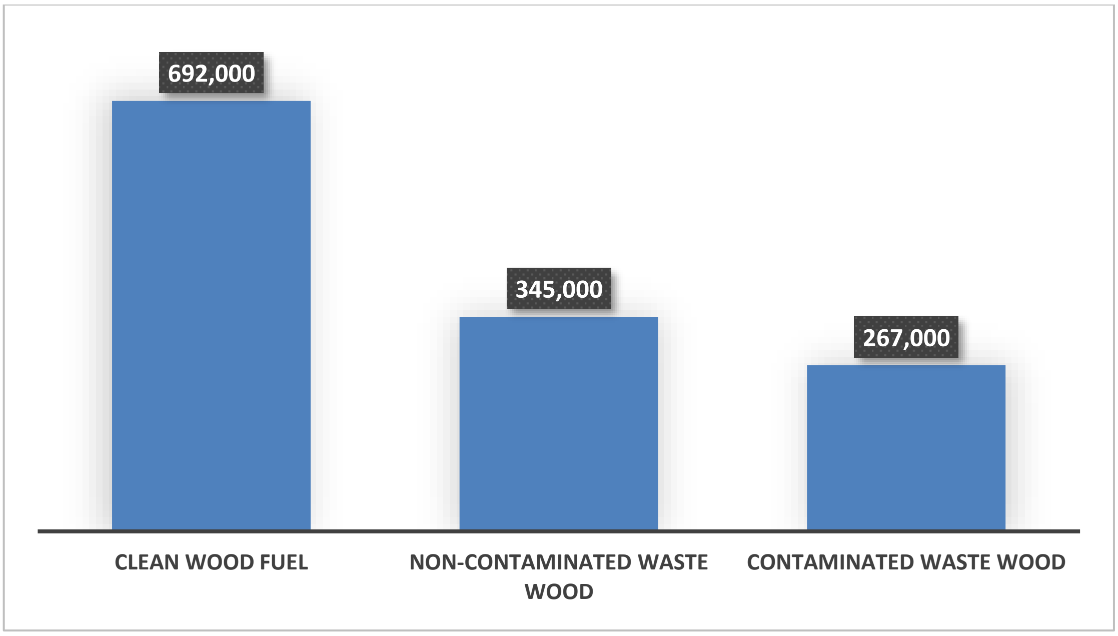


Figure 20: Woody biomass domestically available for bioenergy use in Wales (in tonnes per year) [65]

6.3 BioLPG production potential and strategic locations

Opportunities for valorising domestically available feedstock seem to be limited to around 150,000 tonnes of untreated residual waste that are currently destined to landfill as well as to the 50,000 tonnes of RDF that are exported to countries outside the UK.

In the case of residual waste, recyclable products, and materials not suitable for processing should be removed for the production of RDF before the gasification step. This integrated 'MSW to fuel' business model was first pioneered by Fulcrum Bioenergy, the production facility of which is expected to become operational at the end of 2020, processing around 175,000 tonnes of MSW annually for the production of FT liquids.

Mid & South West Wales seems to be the most attractive location for developing a residual waste processing facility. This region is responsible for the annual generation of more than 100,000 tonnes of residual waste destinated to landfill, which in combination with the exported quantities of RDF, can meet the feedstock requirements of a facility of the size of Fulcrum in Canada for the production of approximately 10,000 to 20,000 tonnes of a mixture of BioLPG and fossil LPG (low carbon fossil fuel), considering the fact that residual waste is partially renewable feedstock; the exact bio-based quantities depend on the energy value of the bio-based component of residual waste compared to the fossil one. Therefore, it is not expected that a facility of this size would be able to result in a 100% BioLPG transition in Wales.

It is important to note that available residual waste volumes are going to decrease, as we go forward, due to increasing recycling and reuse targets. This needs to be taken into consideration as gasification to BioLPG technologies require significant R&D efforts and cannot be realised in the short term. Additional residual waste volumes that are currently destined to 'energy from waste' might be available for longer term production, but this is expected to be subject to existing contracts and the feasibility of this scenario requires further investigation.

A 100% BioLPG transition in Wales can achieved by importing roughly 300,000-1,000,000 tonnes of woody biomass, depending on size of the LPG market in Wales[23]. These requirements can be considered achievable, when considering Drax Power's wood pellet imports of around 7 million tonnes in 2019 [66]. Additional quantities will be required if the aim is to displace high carbon fossil fuels (e.g. heating oil).

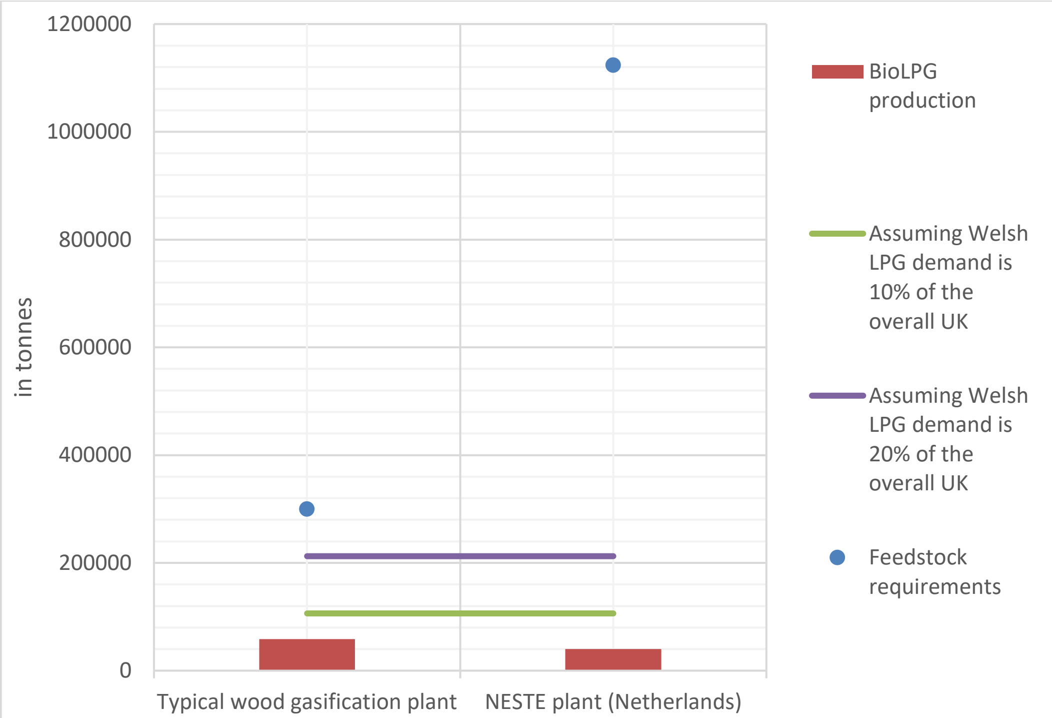


Figure 21: Potentially available volumes from standard sized BioLPG production plants against likely LPG demand in Wales

It is important to note that hydrogenation of triglycerides is the only technology that is currently commercially available and can supply certain BioLPG volumes in the short term, but sustainable waste bio-oil quantities domestically available are not enough to justify the development of a dedicated standalone plant, and any production efforts should be based on imports.

Opportunities exist in utilizing existing capacity of the Pembroke Refinery (Appendix 9), which is the only refinery in Wales with a refining capacity of 270,000 barrels (around 36,000 tonnes) per day[67] , including 220,000 barrels of crude oil and 50,000 of other feedstock, possibly referring to biooils. This available capacity suggests that very large volumes of bio-oils can be co-processed with petroleum intermediates, without reaching any blending limits. This option is particularly attractive because Pembroke refinery already produces fossil LPG and is connected to the LPG distribution network.

[23] LPG demand in Wales is not publicly available, but the two major LPG suppliers in Wales (Flogas and Calor), which are expected to be the main interested parties, will be able to provide some relevant information.

7 BioLPG production opportunities in Northern Ireland

Key findings

- The gas network in Northern Ireland is not as extensive as in Great Britain, and as a result 68% of homes (84% in rural areas) are currently relying on kerosene for their primary source of heating, meaning that BioLPG is more than a promising decarbonisation option for the residential heating sector.
- According to CCC, hybrid heat pumps, combined with biofuels and green gases, have a key role to play in the decarbonisation of off-gas grid buildings in Northern Ireland, while there is also a high potential for biofuels, including BioLPG, to reduce emissions in transport, at least by 2030.
- The major opportunities for BioLPG production in Northern Ireland, using domestically available feedstock, are around the valorisation of residual waste streams through gasification pathways.
    - any efforts for the production of BioLPG using woody biomass, should mostly be based on imports.
- Limited opportunities are also available for the domestic production of HVO diesel and BioLPG as a by-product, mainly due to the absence of oil refining capacity in Northern Ireland.

The gas network in Northern Ireland is not as extensive as in Great Britain, and as a result 68% of homes (84% in rural areas) are currently relying on kerosene for their primary source of heating [68]. The benefits of BioLPG in rural off-gas grid heating applications make it a promising option for Northern Ireland to meet its decarbonisation targets. Indeed, according to CCC, hybrid heat pumps, combined with biofuels and green gases, have a key role to play in the decarbonisation of off-gas grid buildings in Northern Ireland, while there is also a high potential for biofuels to reduce emissions in transport, at least by 2030 [69].

The major opportunities for BioLPG production in Northern Ireland, using domestically available feedstock, are around the valorisation of residual waste streams through gasification pathways. Nearly 141,000 tonnes of RDF were exported from Northern Ireland during the financial year 2018/2019 [70], and their domestic exploitation could lead to the domestic production of roughly 15,000 tonnes of a mixture of bio-LPG and fossil LPG (low carbon fossil fuel), considering the fact that RDF is partially renewable feedstock. Additional quantities of RDF and subsequently LPG could potentially be produced using unprocessed mixed municipal solid waste, currently destined to landfills (figure 22), but higher recycling rates in the future is expected to reduce available volumes.

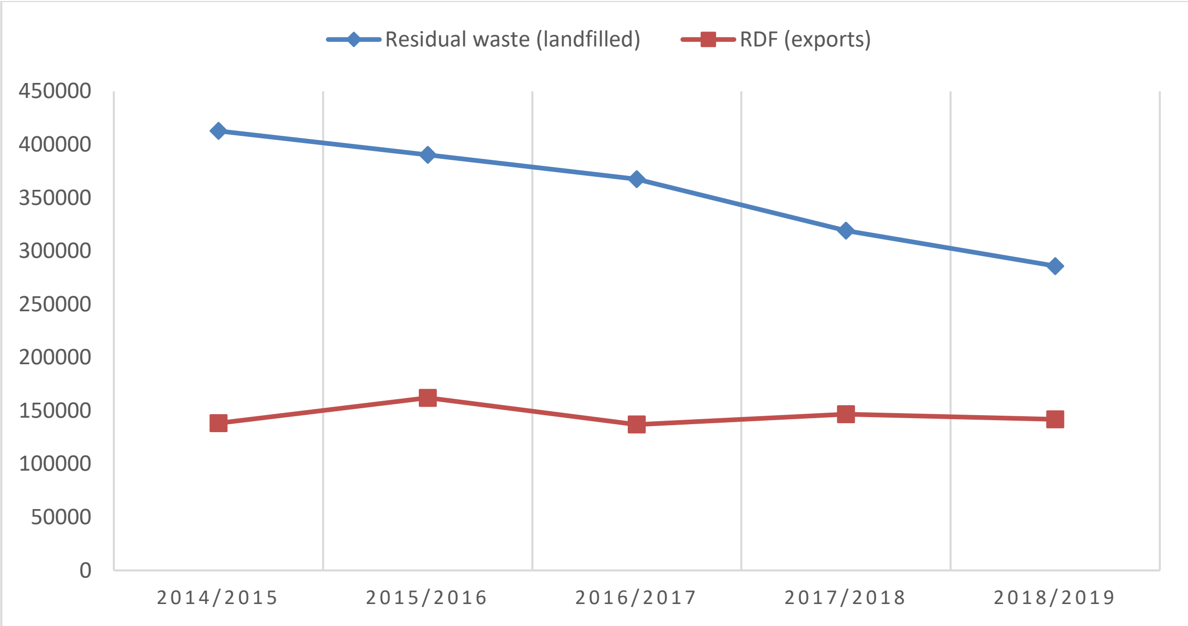


Figure 22: Residual waste volumes destined to landfills and RDF exports in Northern Ireland [70],[71]

Opportunities for utilising sustainable woody biomass, domestically available, are limited to around 132,000 tonnes of waste wood, significant volumes of which are currently recycled or are adequate for recycling. Forestry residues quantities locally produced are expected to be very small. Consequently, any efforts for the production of BioLPG using woody biomass, should mostly be based on imports.

Limited opportunities are also available for the domestic production of HVO diesel, and bioLPG as a by-product, mainly due to the absence of oil refining capacity in Northern Ireland. UCO and tallow production quantities domestically produced are not expected to be sufficient for the development of a dedicated HVO facility, while there are also risks for securing sustainable bio-oil imports at a reasonable price can be considered high, due to competition from global markets.

8 A business case for the development of an indigenous BioLPG supply chain in the UK

Key findings

- There is a credible pathway for achieving a 100% transition to BioLPG in the UK, utilizing domestically available resources and capabilities.
- BioLPG can benefit from existing distribution networks and end-use infrastructure. Consequently, the development of a BioLPG supply chain largely depends on securing adequate volumes.
    - LPG suppliers are currently reliant on imports due to the lack of indigenous production.
- Hydrogenation of bio-oils should be considered the only technology that can potentially displace part of the LPG demand in the UK in the short term.
    - Although BioLPG is produced as a by-product, developing an HVO facility of the size of NESTE's plant, located in Netherlands, could provide adequate volumes for meeting nearly 5% of the total LPG demand in the UK.
    - However, sustainable waste bio-oil quantities domestically available are not enough to justify this level of production.
    - The development of BioLPG production lines inside the six oil refineries, located in the UK, could be an immediately effective solution, minimizing any risks of feedstock supply.
- A 100% transition in the UK would require the development of biorefineries dedicated to BioLPG production, with gasification-based pathways having the highest potential in the mid to long term.
    - A strong contribution is required from Scotland, being by far the most attractive location for the development of wood-based biorefineries. Building 3 standard-sized plants for the production of around 180,000 tonnes of BioLPG, utilizing available woody biomass and diversifying certain sawmill residues volumes from existing uses is feasible.
    - The role of England is expected to be significant mostly due to high amounts of RDF currently exported that can potentially lead to the production of around 300,000 tonnes of a mixture of BioLPG and low carbon fossil fuel.
    - Wales and Northern Ireland can also contribute to BioLPG and low carbon fossil LPG production, but to a lower extent due to limited quantities of residual waste and woody biomass domestically available.
- Isobutene production can also support transition, benefiting from existing sugar beet supply chains in England and/or straw surplus.
- Any feedstock supply gaps towards a 100% BioLPG supply chain can be met through imports.
- As an initial assessment, the investment required for the development of an 100% indigenous BioLPG supply chain in the UK would require somewhere between 1 and 2 billion GBP.
- High revenue streams are expected for supplying BioLPG in the transport market and can justify investments
- The analysis reveals that BioLPG uptake would be an important step for the UK to meet their forthcoming carbon budgets and longer-term net zero targets.
- The indigenous production of BioLPG is expected to result in significant social benefits.
    - Indicatively, a gasification production facility would result in the creation of around 500 jobs during construction, as well as in about 35 full time jobs during its operation.

This chapter examines a credible pathway for the development of an indigenous BioLPG supply chain in the United Kingdom, utilizing the most promising production technologies, with a view of achieving a 100% transition. The investment requirements for the development of BioLPG production facilities are also reviewed along with the benefits for supply chain actors.

8.1 Strategic value chain development

BioLPG is chemically identical to fossil LPG, and therefore can benefit from existing supply and distribution networks, while it is also 100% compatible with end-use infrastructure (e.g. Autogas filling stations, LPG vehicles, and heating boilers). Therefore, the development of a BioLPG supply chain largely depends on the production of adequate volumes to meet current and future demand[24].

8.1.1 Short term production efforts

Hydrogenation of bio-oils should be considered the only technology that can potentially displace part of the LPG demand in the UK in the short term. Using NESTE's plant in Rotterdam as an example, figure 21 shows that although BioLPG is produced as a by-product, developing an HVO facility of this size could provide adequate quantities for meeting nearly 5% of the total LPG demand in the UK[25].

Nevertheless, sustainable waste bio-oil quantities domestically available - around 540,000 tonnes of UCO and tallow without considering competing uses - are not enough to justify this level of production, as NESTE's plant seems to be the largest HVO facility worldwide, and expected to require approximately 1.2 million tonnes of bio-oils to reach capacity. Efforts for the production of a facility of this size should focus on imports. Moderate scale HVO facilities typically require 140,000 to 652,000 tonnes of bio-oil feedstock. Still, securing these volumes at a reasonable cost is expected to be challenging given the high competition in domestic and global markets.

A recent study carried out by GREENEA revealed that the European and UK UCO market is already mature with limited growth opportunities, and in order to secure additional feedstock quantities, developers need to look for alternative sources such as imports from overseas [72]. However, there is a high risk of supply shortage, if high collecting countries (China, US, India) decide to stop the exportation and develop local biodiesel production supply chains [21], like in the case of Asia [73].

The risks of supplying raw materials can be reduced by utilizing existing capacity of oil refineries (hydrotreaters), as refiners have higher flexibility to change feedstocks or vary product specifications in response to market movements. Six oil refineries are located in the UK, with capacity to co-process large quantities of bio-oils with petroleum intermediates, without reaching any blending limits. This option is particularly attractive because oil refineries already produce fossil LPG and are connected to the LPG distribution network.

[24] In the case of adequate BioLPG volumes available in the market, the end-use infrastructure can rapidly be expanded at a minimal cost as: a) new LPG vehicles are already available in the market alongside conversion kits for retrofitting used vehicles, b) Autogas refuelling stations can rapidly be expanded at no cost to the taxpayer, c) there is also an existing network that offers expertise on LPG boiler installations to the most current standards.
[25] According to data provided by Liquid Gas UK, the UK LPG demand is around 1 million tonnes per year.

Consequently, the development of a BioLPG production lines inside oil refineries could be immediately effective solution. Efforts should focus on engaging refineries and securing a sustainable feedstock supply at a reasonable price, which is expected to be an ongoing challenge. Opportunities for increasing the availability of sustainable feedstock include the acquisition of UCO exporters as well as the development of a pre-treatment unit to enable the co-processing of high acidic feedstock.

8.1.2 Mid- to long-term production efforts

A 100% transition in the UK would require the development of multiple biorefineries dedicated to the production of BioLPG, with gasification-based pathways having the highest potential. Figure 23 presents a pathway for the production of BioLPG using domestically available resources in each of the 4 UK Nations and imported biomass.

A strong contribution is required from Scotland, being by far the most attractive location for the development of wood-based biorefineries. Building 3 standard-sized plants in the strategic locations presented in Appendix 10, for the production of around 180,000 tonnes of BioLPG, utilizing currently available woody biomass after competing uses (mostly forestry residues), and diversifying certain sawmill residues volumes from existing uses can be considered feasible. This is because large woody biomass quantities are available in Scotland and competing uses are likely to be price dependant [50].

Relatively high amounts of RDF available in Scotland can also lead to the production of around 19,000 tonnes of BioLPG and similar quantities of LPG, classified as a low carbon fossil fuel. A strategic location, with good access to ports and residual waste availability, for the development of a residual waste plant is presented in Appendix 8.

The role of England will be significant in this transition, mostly due to high amounts of RDF currently exported abroad that can potentially lead to the production of around 300,000 tonnes of a mixture of BioLPG and low carbon fossil fuel. Additional volumes can be produced through the diversification of residual waste from landfills and 'energy from waste'. Two strategic plant locations that require further investigation, are also presented in Appendix 8.

This potential can be supported by isobutene production through the fermentation of sugars. In collaboration with Crystal Union, the technology developer (Global Bioenergies) is planning to commission a 'First of a Kind' facility with production capacity of 50,000 tonnes using sucrose as feedstock, outside the UK. Therefore, the development of a follow-up facility of twice the size in Eastern England, where the production of crystalline sugar is based, is expected to be a realistic scenario, given that feedstock availability (sugar beet) is not expected to be a factor that can limit deployment, while isobutene is not a subject of a crop-cap, if used in the heating market. Additional BioLPG quantities can be produced by exploiting straw resources available in Eastern England, East Midlands, and Yorkshire, for the production of a second-generation biofuel.

Wales and Northern Ireland can also contribute to BioLPG and low carbon fossil LPG production, but to a lower extent. Figure 23 only presents the LPG potential using RDF quantities that are currently exported from both Nations, but the diversification of residual waste volumes currently destined to landfill or 'energy from waste' for the production of RDF and subsequently of LPG can increase the overall potential.

Meeting existing LPG demand would require additional BioLPG quantities to be produced, possibly using imported woody biomass, roughly 1,600,000 tonnes. These requirements can be considered feasible, when considering Drax Power's wood pellet imports of around 7 million tonnes in 2019 [46]. Additional quantities will be required if the aim is to displace high carbon fossil fuels (e.g. heating oil), while any gaps for achieving a 100% BioLPG transition can be always be met through BioLPG imports.

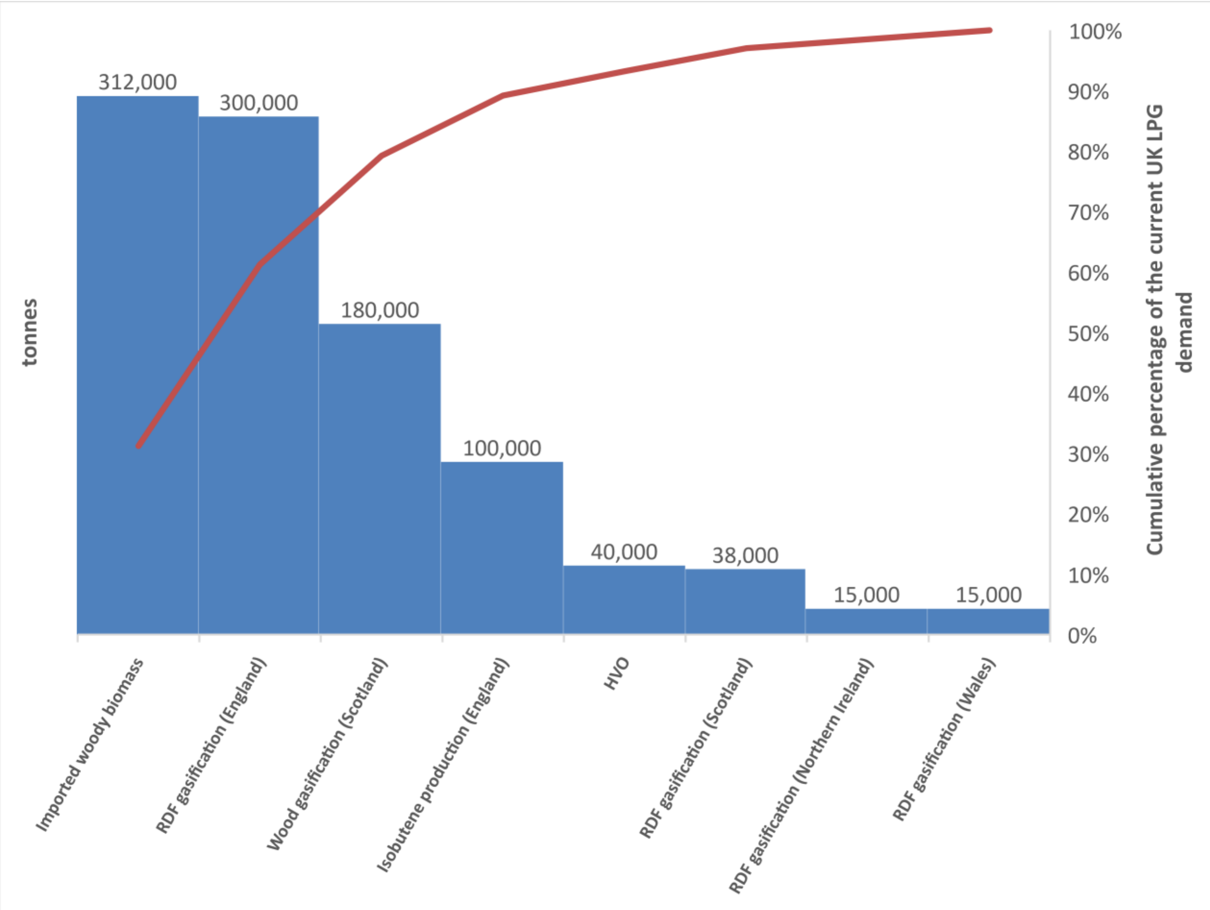


Figure 23: A credible pathway for the production of BioLPG using domestically available resources and imported biomass

It should be noted that this production potential cannot be realised in the short term, as gasification-based pathways for the production of BioLPG, as a main product, appear to be at an early stage of development. The syngas-methanol-DME-BioLPG route appears to be the mostly developed gasification pathway for the production of BioLPG, and industrial efforts should focus on testing the fully integrated process in an operational environment, which is expected to be achievable within the next decade using existing conversion technologies. In collaboration with technology developers, interested parties can also investigate whether commercially viable routes are feasible for gasification-based pathways that focus on BioLPG direct synthesis, by adapting FT and BioSNG production catalysts. The development of catalysts with high selectivity for the production of BioLPG is of utmost importance. Similarly, the isobutene production pathway also need to be demonstrated on an industrial scale, which is expected in the mid-2020s.

8.2 Investment requirements for establishing a BioLPG supply chain

Co-processing of bio-oils with petroleum intermediates in oil refineries for the production of renewable diesel, requires almost no additional capital cost, apart from any requirements for feedstock pre-treatment, which is estimated to be around 4.6 million euros (around 4.14 million GBP) [74][26]. It is also expected that oil refineries already have the capabilities to recover and purify the bio-propane component for the production of a fuel that meets LPG specifications[27]. Therefore, oil refineries can process very high quantities of bio-oils with minimal capital expenditures.

In contrast, building a new dedicated HVO unit would require significant investments which range from 98 to 707 million euros (89.9 to 648.6 million GBP), depending on plant capacity, while an additional investment is required for separating BioLPG from the off-gas stream produced as a by-product [74]. According to Neste, the investment cost of their bio-LPG separation and purification unit in Rotterdam, with a production capacity of 40,000 tonnes, was 60 million Euros (55 million GBP).

As a side note, investment decisions are primarily driven in both cases by the competitiveness of renewable diesel. A competitive advantage is expected in the case of producing renewable fuel through co-refining due to significantly lower capex needs and considering that hydrogenation requirements of bio-oils for the production of diesel will be the same. Still, based on a study conducted on behalf of BEIS [75], feedstock costs appear to be by far the largest contributor of the overall production, around 70% including depreciation and capital costs, and therefore can determine to a great extend the competitiveness of the final biofuel.

Even though there are opportunities for producing certain BioLPG quantities with minimal capital costs through the co-processing model, achieving a 100% transition to BioLPG in the UK would require significant investments in gasification based biorefineries. Based on the CAPEX data publicly available from gasification project developers, building an industrially sized gasification and catalytic synthesis facility, is expected to require around £100 to £200 million.

It should be noted that gasification plants presented in table 4, are not designed to produce BioLPG as a fuel output, but costs to produce BioLPG are expected to be analogous. The design of a BioLPG plant can be similar to the designs developed by APP and Peel L&P for the production of BioSNG through direct synthesis, as the gasification and syngas clean-up process will be identical, while the complexity of the catalytic conversion step is expected to be comparable, due to the similar structure of the two molecules.

Considering the syngas-methanol-DME-BioLPG route, the capital cost requirements for building an integrated facility is expected to be comparable to Enerkem's bio-methanol production plant in Netherlands, which is currently in application stage of development. Nevertheless, additional capital expenses are required as the ultimate goal is the production of DME or BioLPG, and methanol should be seen as an intermediate product.

[26] Assuming 1 GBP=1.0996 Euros (03/08/2020)

[27] There are no additional costs for separating the bio and fossil fractions as they can be kept administratively segregated using the mass balance principles. Mass balance systems are currently permitted under the RED II (2018/2001/EU), and are also accepted by RED compliant voluntary schemes, like ISCC and RSB, which give general guidance on how these systems will be implemented.

Table 4: Indicative capital costs and capacities of major gasification project developers

Developers	Technology	Location	Status	GWh/a	Tonnes	CAPEX	Ref.
Enerkem	Gasification and methanol synthesis	Canada	First of a Kind	165	30,000	£46,300,000 (from CAD**)	[76]
Enerkem	Gasification and methanol synthesis	NL	Commercial	1211	220,000	£202,500,000	[76]
Peel L&P	Gasification and SNG synthesis	UK	First of a Kind	320	22,000	£150,000,000	[77]
APP	Gasification and SNG synthesis	-[28]	First of a kind	315	21,656	£107,900,000	[78]
APP	Gasification and SNG synthesis	-	Commercial	665	45,718	£150,700,000	[78]

* CAD to GBP conversion rate: 0.57 (03/08/2020)

Finally, in terms of the CAPEX requirements for the development of an isobutene facility that can support the production of BioLPG from gasification and HVO pathways, Global Bioenergies estimates that a 50,000 tonnes unit will cost around 100 million Euros (around 90 million GBP[29]) [79].

Even though, they can give a good indication of the amount of investment required, cost figures collected in the present study should be treated with caution, as detailed techno-economic assessments would be required - to consider for example the effects of scaling and location - in collaboration with technology developers, prior to investment decisions. As an initial assessment, the investment required for the development of an indigenous BioLPG supply chain in the UK would require somewhere between 1 and 2 billion GBP.

8.3 Economic benefits for supply chain actors

At the current time, transport is by far the highest value market for BioLPG suppliers, due to the financial incentives provided by the RTFO in the form of RTFCs. BioLPG is not an eligible fuel for receiving RHI support in domestic and non-domestic heating applications. Therefore, suppliers would be only able to market bioLPG at the same price as its fossil alternative, unless an end-user is willing to pay a price premium for greening their supply chain[30].

Figure 24 presents additional income that can potentially be received by supplying BioLPG in the transport market depending on the fuel status (crop-derived[31], and general). Even though both RTFCs and GHG credits are awarded to BioLPG suppliers when the fuel crosses the duty point of the supply chain, which is normally as it leaves the refinery, the value is reflected on the price of BioLPG at the factory gate, meaning that BioLPG will be sold at a higher price compared to its fossil alternative, and

[28] Advanced Plasma Power (APP) CAPEX values are based on modelling of the technical performance of large-scale facilities and informed by the engagement with equipment suppliers.

[29] Assuming 1 GBP=1.0996 Euros (03/08/2020)

[30] While transport market is expected to remain the mostly incentivised market until 2032, when the current Renewable Transport Fuel Obligation (RTFO) levels expire, priorities may change as we go forward due to the need for each energy source to be used in the most efficient manner, so that its decarbonisation potential is maximised.

[31] Although not expected to be part of the final biofuel production mix, the income from the supply of crop derived BioLPG is also presented to enable comparisons.

producers can also be compensated for higher production costs. However, these mechanisms do not necessarily incentivise an indigenous BioLPG production, as policy wise it does not make a difference if the BioLPG is produced domestically or it is imported. Hence, mechanisms within the UK at the local level, such as zero planning constraints could make a big difference to the project developer.

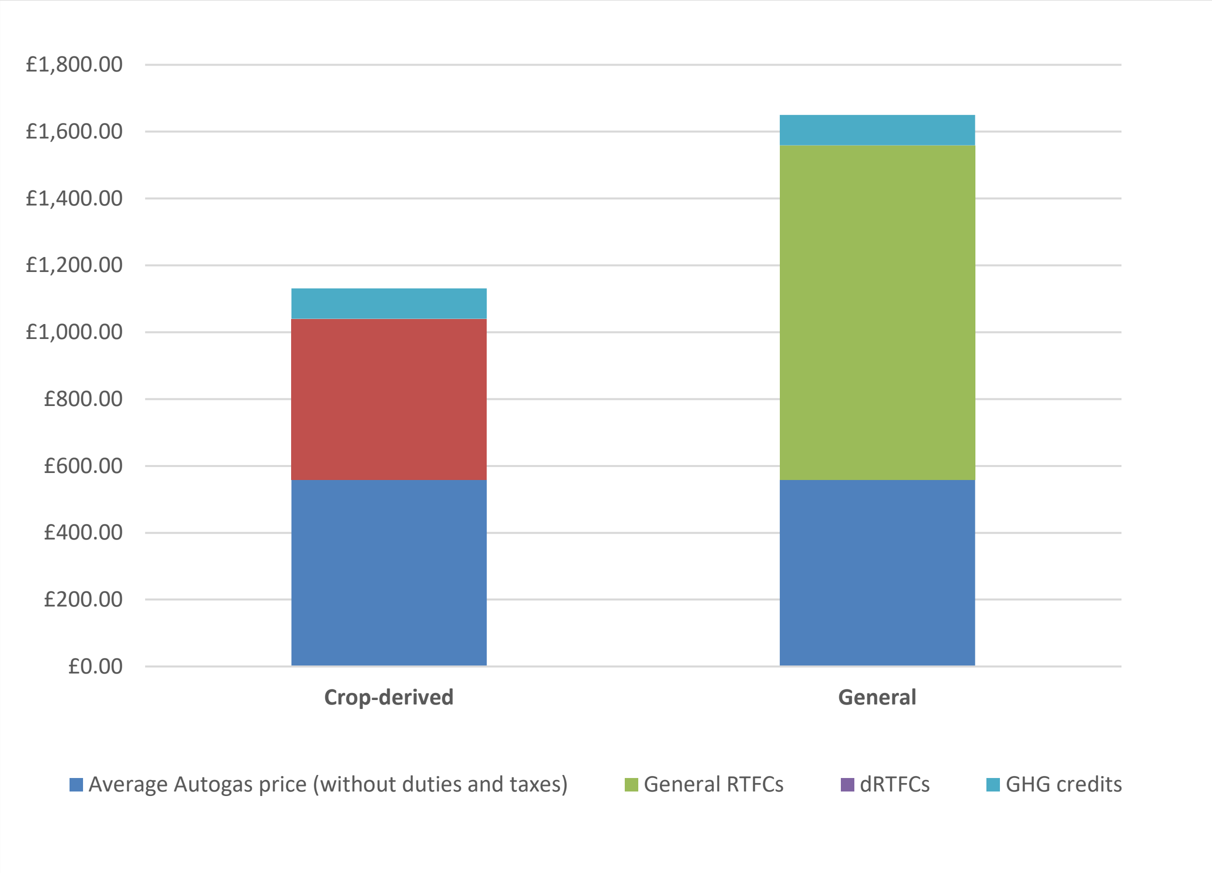


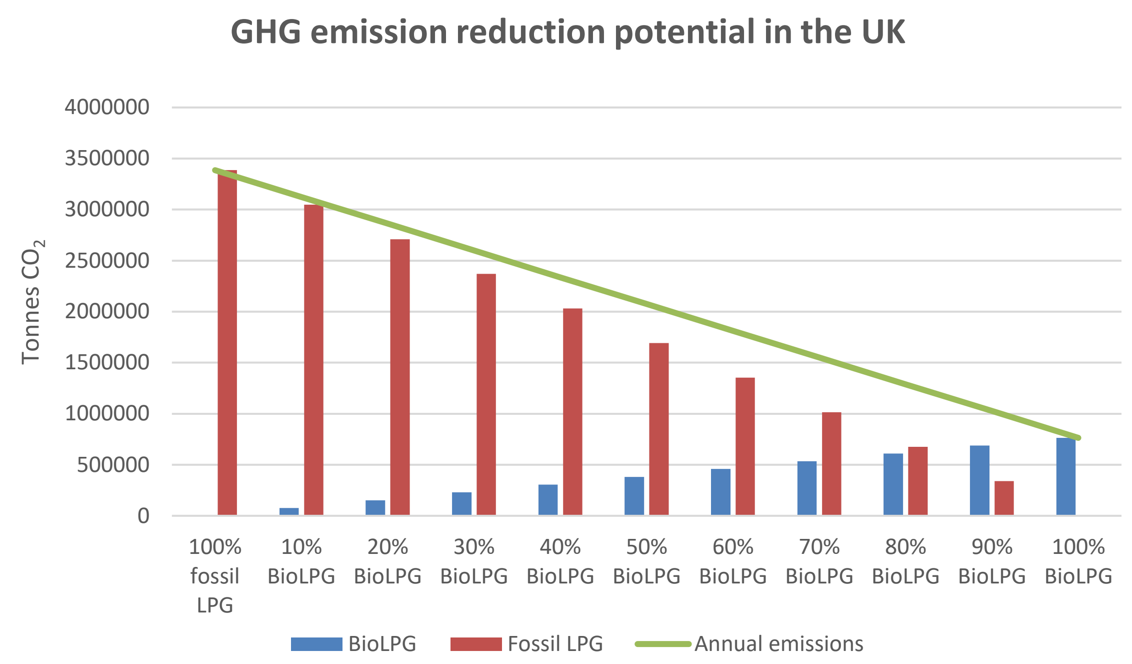
Figure 24: Income for supplying one tonne of BioLPG in the transport market

8.4 Potential GHG savings and social benefits

The indigenous production of BioLPG is expected to result in significant social benefits. Indicatively, based on information provided by a BioSNG project developer, a gasification production facility would result in the creation of around 500 jobs during construction, as well as in about 35 full time permanent jobs during its operation [80][32].

Figure 25 also presents the GHG emission reduction potential in the UK by shifting existing fossil LPG consumption to BioLPG. It is clear that the BioLPG uptake would be an important step for the UK to meet their forthcoming carbon budgets and longer-term net zero targets.

[32] It should be noted that the organisation of a BioLPG production lines inside oil refineries is not expected to lead to significant job creation.



Assumption: GHG intensity of BioLPG: 16.6 g CO_2eq/MJ
(Data source: Bilans-GES's resource centre)

Figure 25: GHG emission reduction potential in the UK using different mixtures of LPG/BioLPG

9 SWOT analysis

Drawing on the preceding analysis, the following SWOT analysis summarises the key parameters affecting the development of an indigenous BioLPG supply chain in the UK.

Table 5: SWOT analysis

Strengths	Weaknesses
• BioLPG is chemically identical to fossil LPG, being 100% compatible with existing supply networks and end-use infrastructure. • BioLPG liquefies at a relatively low pressure at room temperature, which allows its cost-effective distribution and storage in off-gas applications. • BioLPG offers a cost-effective decarbonisation solution in off-gas grid buildings that are not suitable for an electrical solution. • BioLPG results in substantially reduced PM and NO_x emissions compared to solid and liquid fuels.	• Only the HVO process has a high technology readiness level, where BioLPG is produced as a by-product in relatively low quantities. • Investment decisions in HVO facilities are primarily driven by the competitiveness of renewable diesel as the main product. • A 100% BioLPG transition requires the development of technologies that target BioLPG as primary product. • BioLPG is not an eligible fuel for receiving RHI support in domestic and non-domestic heating applications.
Opportunities	**Threats**
• UK has a high proportion of users in off the gas grid rural areas, where electrification is more difficult and expensive. • Large volumes of bio-oils can be co-processed with petroleum intermediates to produce BioLPG in existing UK oil refineries, at almost no additional capital cost. • Gasification technologies can produce sufficient BioLPG quantities for meeting LPG demand in the UK using domestically available feedstock. • Isobutene production can support a transition to 100% BioLPG, benefiting from existing sugar beet supply chains in Eastern England. • High financial incentives are provided by the RTFO for supplying BioLPG in the transport market. • Indigenous production will result in the creation of green jobs and support the UK to meet its decarbonisation targets.	• Securing sustainable bio-oils (UCO and tallow) would be an ongoing challenge due to limited domestically available feedstock in the UK and high competition in global markets. • Advanced BioLPG production technologies do not reach a commercial stage of development or do not demonstrate that commercially viable routes are feasible. • BioLPG uptake is not a priority in future UK policy support schemes. • Limited available feedstock (e.g. woody biomass and RDF) is used in the production of alternative advanced biofuels or chemicals.

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11 Appendices

Appendix 1: Indicative costs, efficiencies, and GHG emissions for different heating systems

Technologies	Capex (including installation costs)	System efficiency (%)	Fuel cost, (£/kWh)	CO_2 emission factor, (kgCO2/kWh)
Standard boiler	5,717	75	0.063	0.26627
New oil boiler	4,900	88	0.063	0.26627
LPG boiler	4,000	92	0.067	0.21447
BioLPG boiler	4,000	92	0.073	0.06
Biomass boiler	39,235	80	0.055	0.01506
High- Stated efficiency heat pump	27,300	300	0.144	0.06809
Typical in-situ electric heat pump	27,300	265	0.144	0.06809

*Table data source: [6]

Appendix 2: Indicative levelized cost of different heat technologies

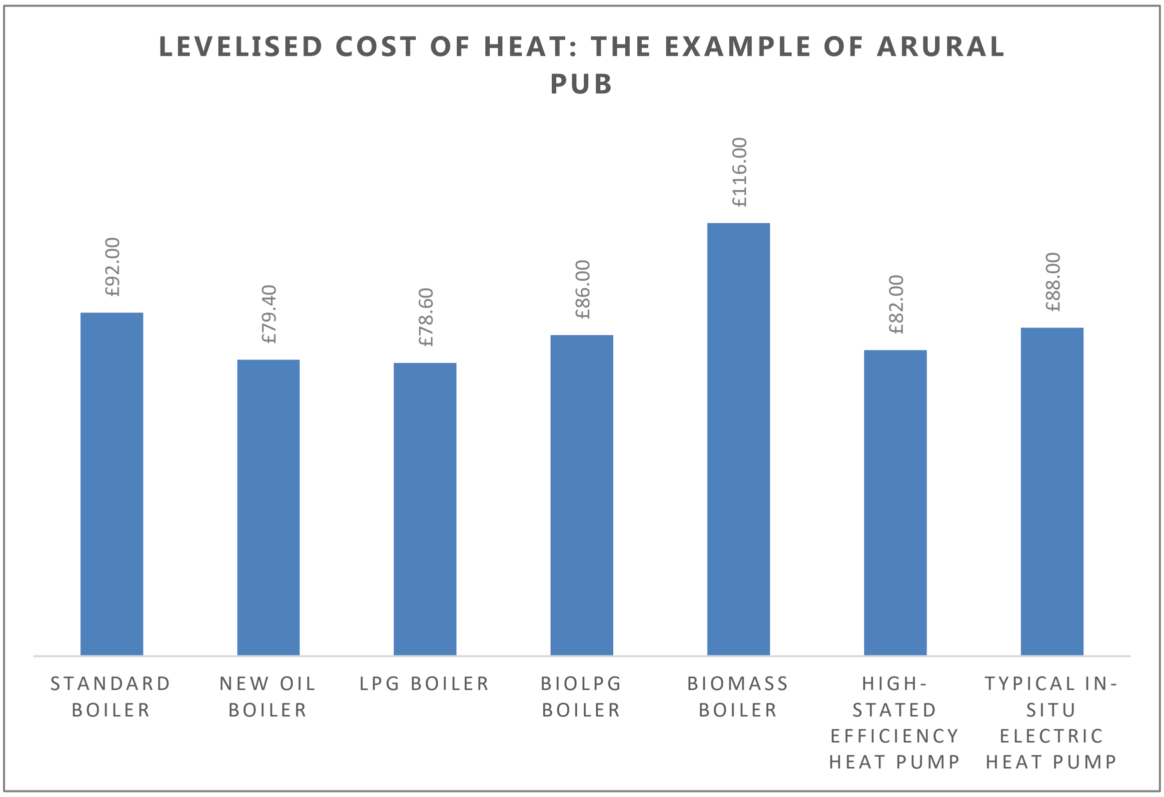

*Table data source: [6]

Appendix 3: The Renewable Transport Fuel Obligation

The Renewable Transport Fuel Obligation (RTFO) [9] is the UK Government's principle policy for reducing greenhouse gas emissions from fuel supplied for use in road vehicles and non-road mobile machinery. Under the RTFO Order, fuel suppliers have an obligation to provide a volume of sustainable renewable fuels which is calculated as a proportion of the overall volume of fuel they supply for road transport and NRMM purposes[33].

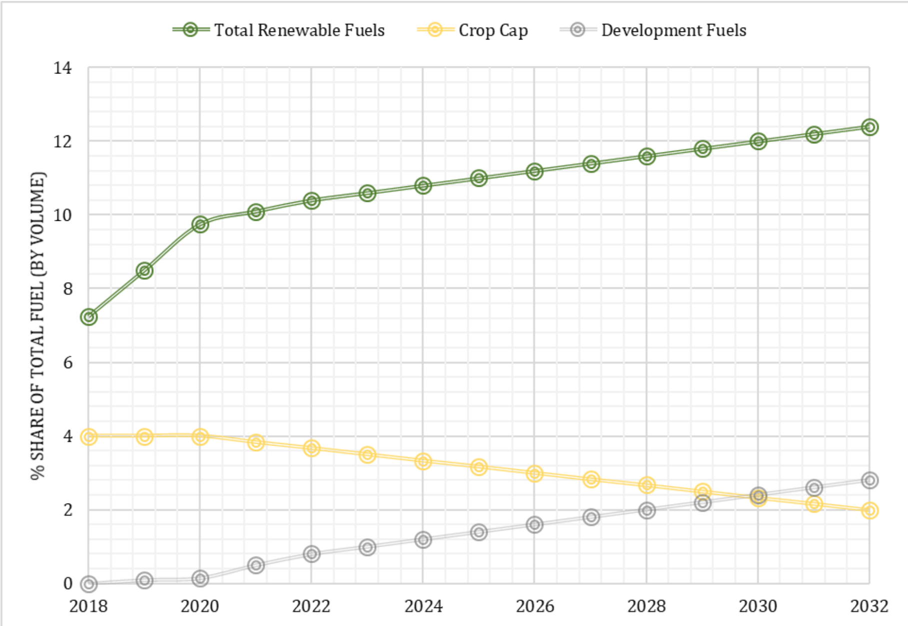

Figure 26: Obligated RTFO targets for sustainable fuels.

To demonstrate compliance with the obligation, fuel suppliers must redeem sufficient renewable transport fuel certificates (RTFCs) or pay a 'buy-out' fee of 30 pence per certificate. One RTFC is issued per litre of liquid renewable transport fuel supplied at the duty point, regardless of whether the supplier has an obligation under the Order. In the case of gaseous fuels, RTFCs are awarded on a kg basis, reflecting the energy density of the gas compared to an average biofuel; BioLPG is rewarded at 1.75 RTFCs per kg. It should be noted that double RTFCs are issued for fuels produced from certain double counting feedstocks (e.g. wastes and residues).

A crop cap was introduced on the 15 April 2018, which sets an upper limit, by volume, on the contribution that crop-derived biofuels can make towards discharging a supplier's obligation. That limit is equivalent to a certain proportion of their total relevant fuel supply and will start to decrease every year from 2021 to reach 3% by 2026 and 2% by 2032, as set out in figure 26 above.

A target for a specific sub-set of advanced fuels termed 'development fuels' was also introduced in 2019 from 1 January 2019. This target considers the fuel type, production pathway and the feedstock, so as to incentivise those fuel pathways which need greater support and fit the UK's long-term strategic needs; eligible development fuel types are defined in figure 27. Development fuels are

[33] From 15 April 2018, renewable fuel used in aviation in the UK is also eligible for reward under the RTFO, although fossil aviation fuel is not obligated.

supported by a higher buyout price of 80 pence per certificate, with 2 certificates awarded per litre, providing support of up to £1.60 per litre. BioLPG does not meet eligibility criteria for development fuels.

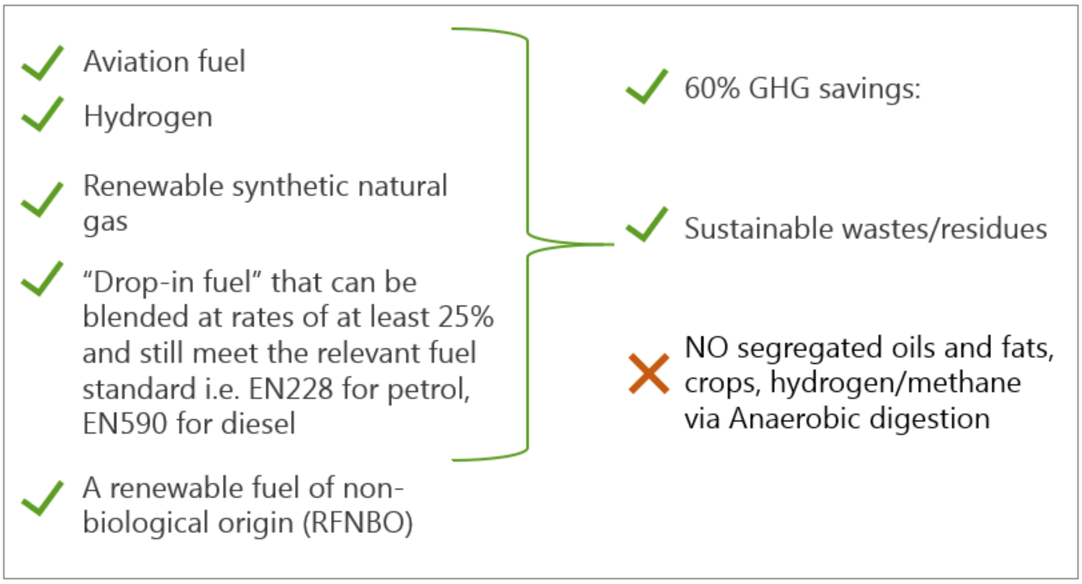

Figure 27: Eligibility criteria for development fuels

The above-mentioned targets have led to the introduction of cRTFC (crop derived), RTFC ('normal' or 'waste'), and dRTFC (development fuel certificates) reflecting their different trading values on the open market.

Finally, it should be noted that fuels supplied for being eligible for RTFCs must meet mandatory sustainability criteria. Fuels must achieve a minimum GHG saving of either 41.9gCO2eq/MJ (if operational on or prior to 5 October 2015 - equivalent to a 50% GHG saving) or 33.52gCO2eq/MJ (if operational after 5 October 2015 - equivalent to a 60% GHG saving), while crops used to produce bioLPG must meet certain land criteria and the fuel will also contribute towards the crop cap.

Appendix 4: Location of LEPs

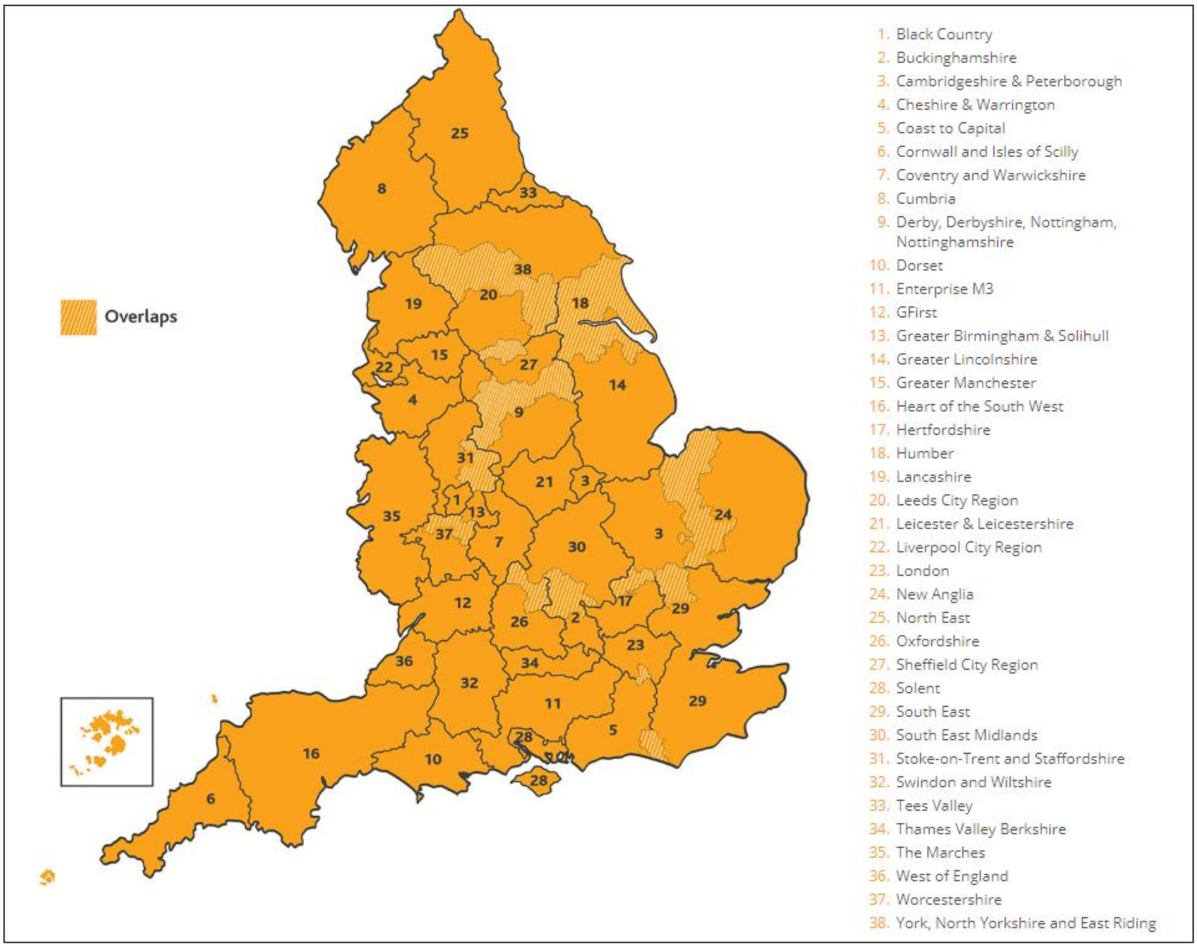

Figure 28: Location Map of LEPs [81]

Appendix 5: Potential funding opportunities in each Devolved Administration

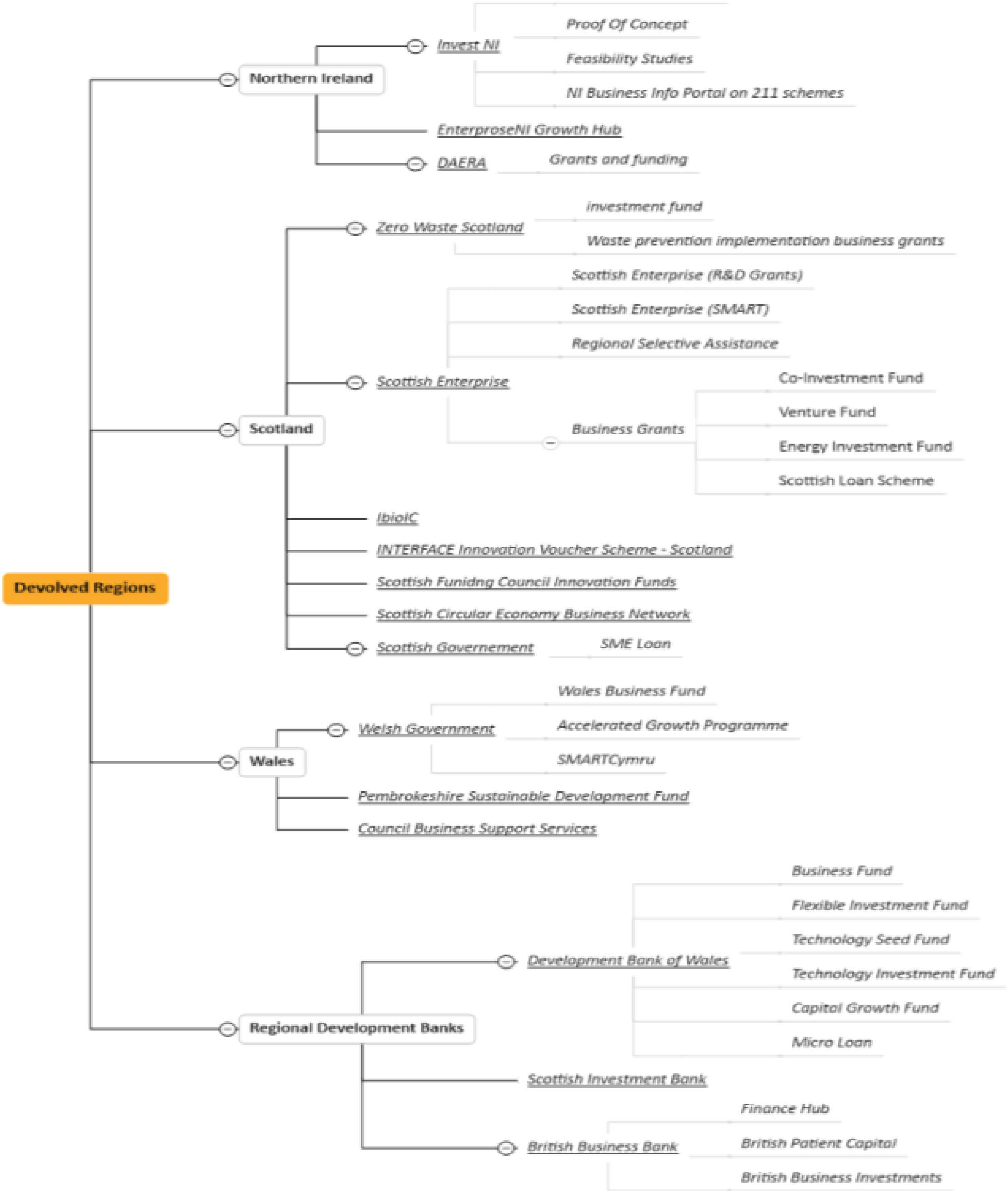

Figure 29: Funding opportunities in each Devolved Administration [82]

Appendix 6: BioLPG production technologies with limited potential

Dehydration of glycerol

Dehydration of glycerol (aka glycerine) is another pathway for the production of biopropane. Glycerol is a major by-product from the production of FAME, with a mass yield of 10% per unit of biodiesel produced. It has a similar chemical structure to propane, and thus the conversion yields are expected to be very high in comparison to other processes. Two organisations, Biofuels Solutions, and the Renewable Energy Group, are active in this area, but production is not yet commercialised.

Due to the rapid development of the biodiesel market, initially more glycerine was produced than the market could absorb. However, with the growing number of possible applications, the demand for glycerine began to increase, and the available evidence shows that it has exceeded the current supply [83]. Therefore, although about 18,000 tonnes of glycerol are expected to be annually produced as by-product at the biodiesel plant at Motherwell in Scotland, opportunities for BioLPG production are expected to be limited due to the evolvement of higher value markets (figure 29).

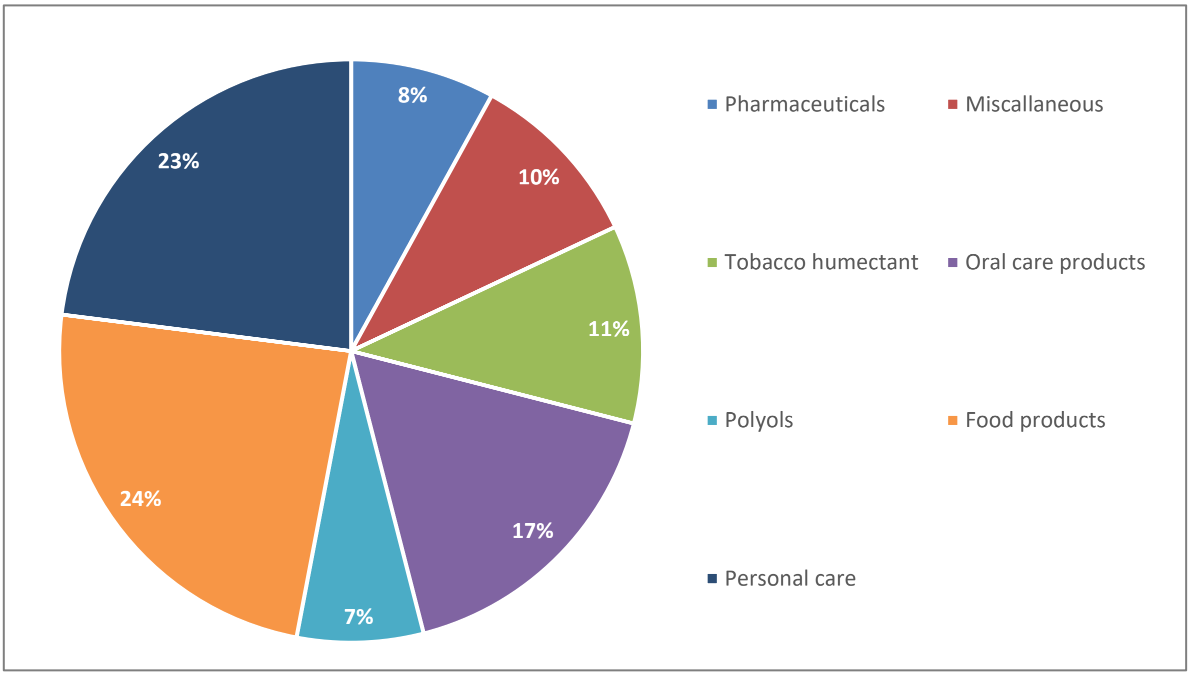

Figure 30: End use of refined glycerine worldwide [83]

Aqueous phase reforming

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. This process has relatively 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 BioLPG yield (C3 and C4 hydrocarbons) is currently not available, but it is expected to be relatively low to recover, and if the process is successfully commercialised, it will be used as a process fuel [84].

Appendix 7: Rendering plants in the UK

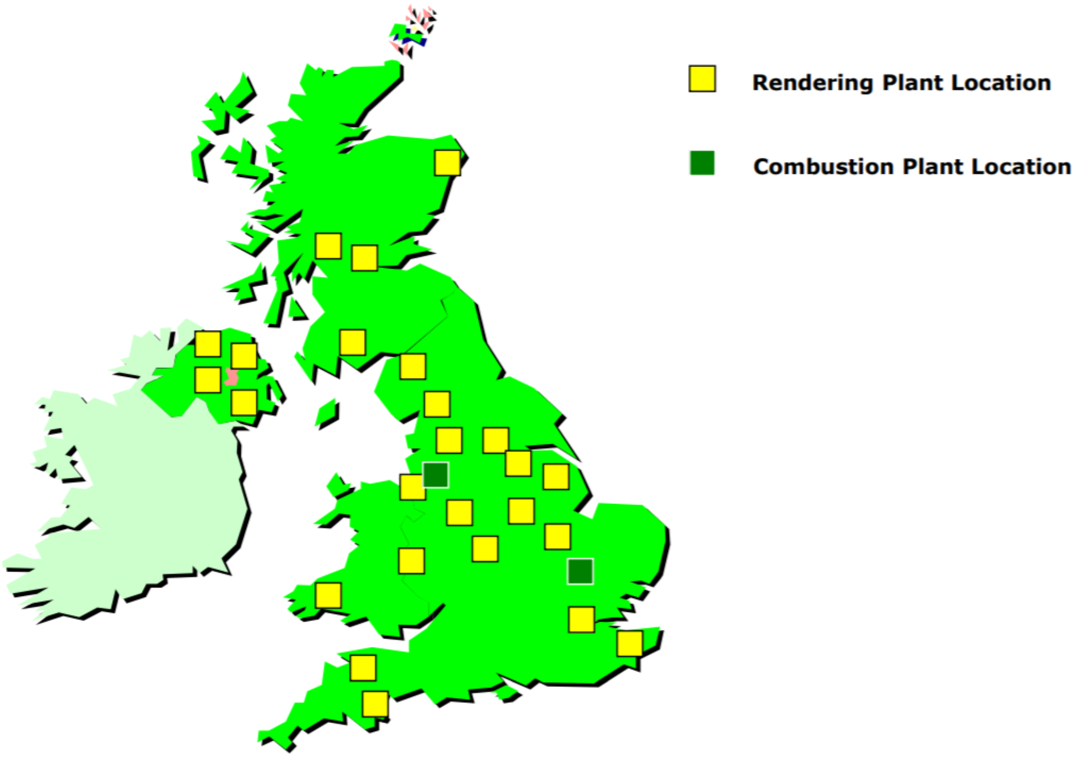

Figure 31: Rendering plants in the UK [59]

Appendix 8: Proposed plant locations for using residual waste in the UK

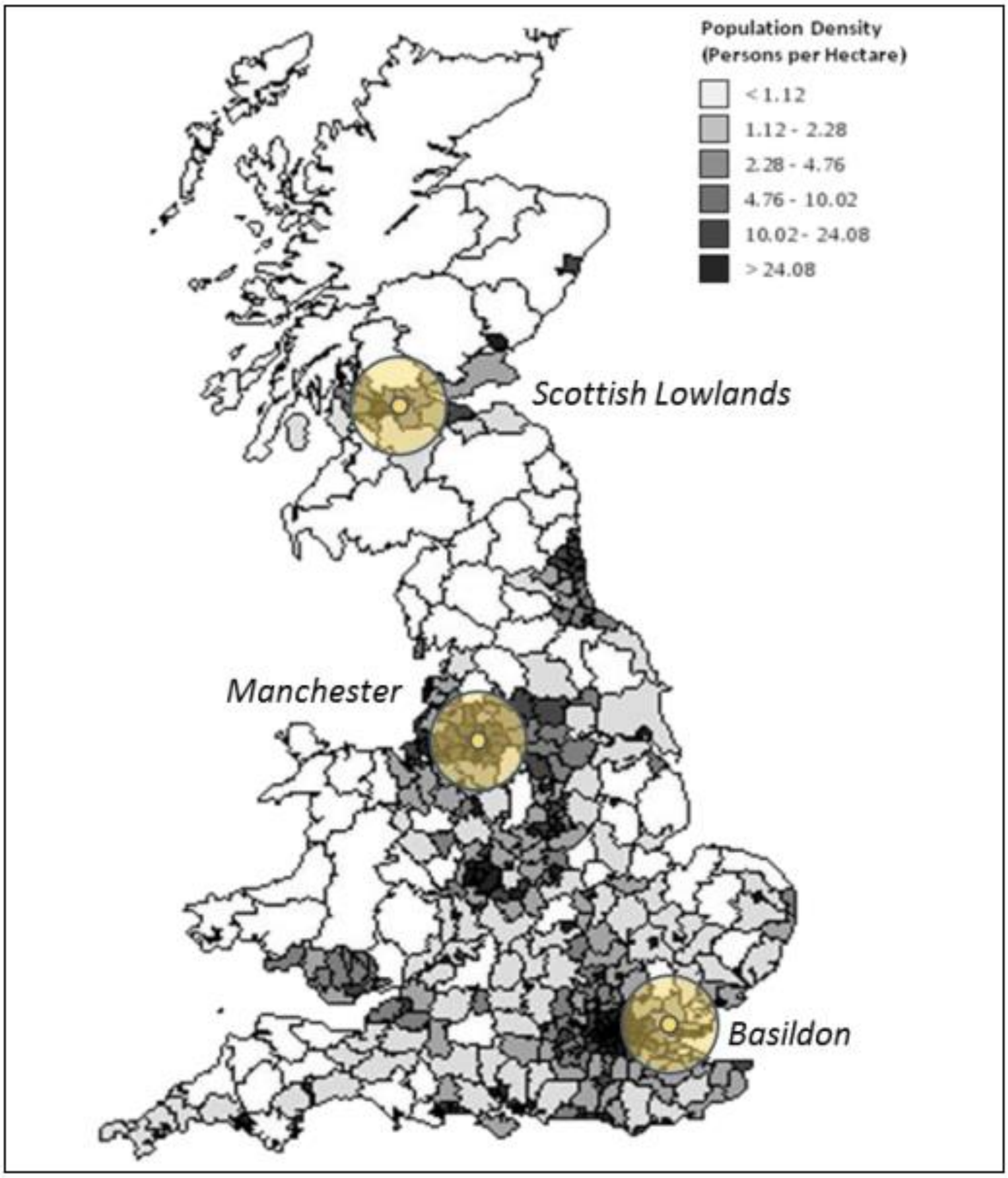

Figure 32: Proposed plant locations for using residual waste in England and Scotland [41]

Appendix 9: Oil refineries in the UK

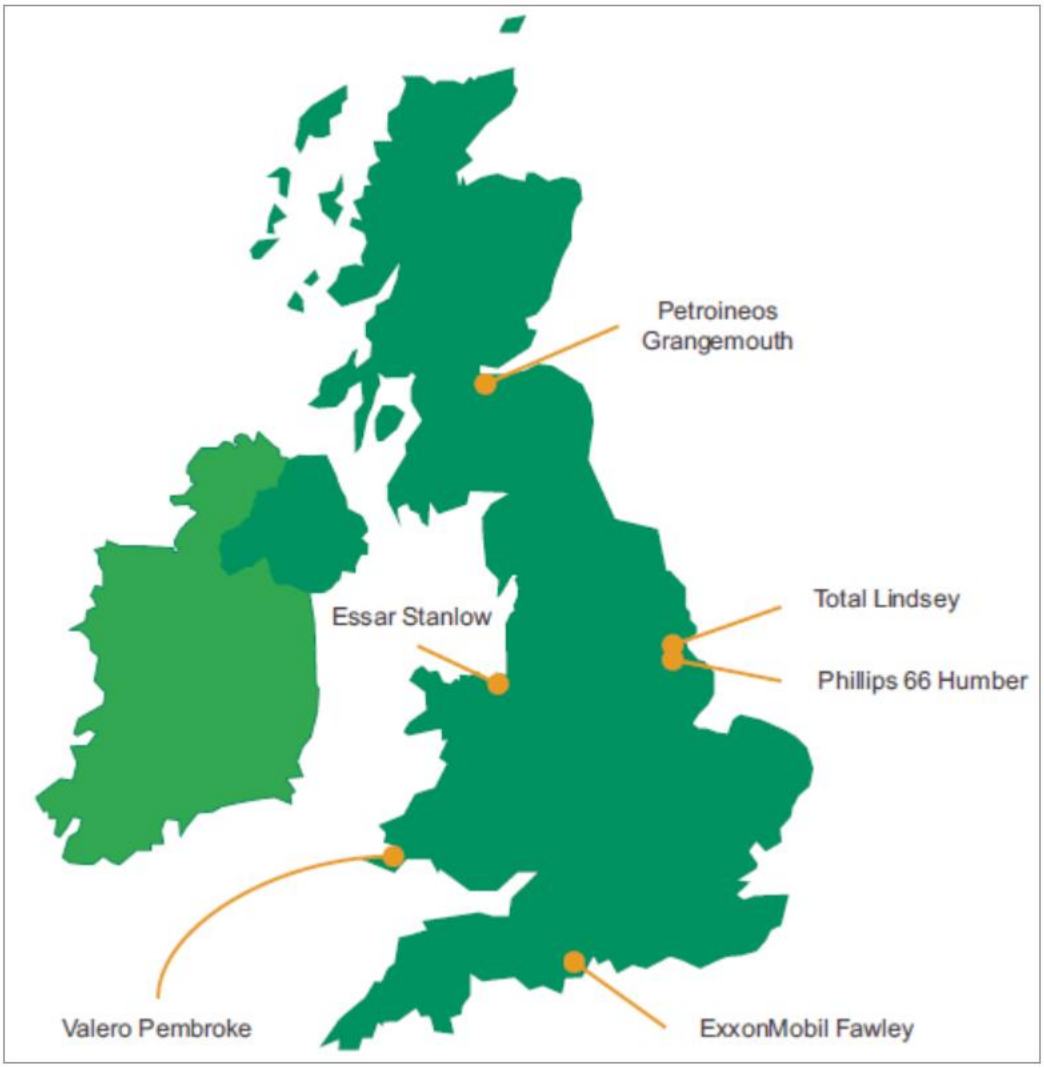

Figure 33: Oil refineries in the UK [85].

Appendix 10: Proposed plant locations for using forest residues in Scotland

Figure 34: Proposed plant locations for using forest residues (yellow), with major forest areas (green) and competing plants (red) [41]

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

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