Low-carbon transport fuels – an evidence review

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1 Executive summary

Emissions from transport must reduce significantly to achieve Scotland's target of net zero greenhouse gas (GHG) emissions by 2045. While Transport Scotland states that zero-emissions solutions are preferable (such as battery and fuel cell electric vehicles, and direct electrification) these are not feasible in some sectors such as aviation and shipping.

In these situations, low-carbon fuels (LCFs), which emit less GHG than fossil fuels, may be more appropriate. The type of feedstock and the conversion technology used to produce the fuel affects the amount of GHG that is emitted.

The purpose of this report is to review the evidence and policy surrounding LCFs in transport.

1.1 Main findings

Bioethanol and Fatty Acid Methyl Ester (FAME) biodiesel are the two main LCFs used in transport in the UK, according to Renewable Transport Fuel Obligation (RTFO) statistics. These are used almost exclusively in road transport and are blended in low volumes with fossil petrol and diesel respectively. The demand for these LCFs is likely to be maintained in the medium term, as increased obligations under the RTFO somewhat offset reduced demand due to increased use of electric vehicles.

Forecasts from the Climate Change Committee's Sixth Carbon Budget suggest that the demand for LCFs in the aviation and maritime sectors in Scotland will increase significantly by 2050, as they are the most viable option to decarbonise these sectors. Given that neither bioethanol nor FAME are suitable for use in aviation, diversification of the LCFs available on the market is essential.

Available feedstocks and conversion technologies

An example of feedstocks that suit Scottish conditions and yet highlight the complexities behind feedstocks and conversion technologies are perennial energy crops, such as miscanthus, tree plantations and short rotation coppice. These are a potentially significant feedstock for biofuel production in Scotland. They could be used to produce LCFs for road transport or aviation, although they have been excluded from the sustainable aviation fuels mandate, which could significantly reduce incentive to convert land to growing these crops.

In spite of the potential, only a small amount of energy crops are grown in Scotland and those that are grown are used to generate heat. This has two implications. Firstly, there is significant uncertainty about the quantity of perennial energy crops that could be available in the future - this is highly sensitive to policy. Secondly, there will likely be strong competition for this feedstock from the heat/power sector, particularly if Scotland's Bioenergy Carbon Capture and Storage (BECCs) ambitions are to be realised.

The potentially abundant supply of renewable electricity in Scotland is a major asset. This could be used to produce green hydrogen, which can either be used as a fuel directly, or combined with captured CO_2 or nitrogen to produce synthetic low-carbon fuels. Green hydrogen and such derivatives are known as renewable fuels of non-biological origin (RFNBOs), which generally offer greater carbon savings compared to biofuels and the third category of LCFs, recycled carbon fuels (RCFs). RFNBOs are a particularly attractive option to decarbonise aviation where available quantities of suitable biofuel and RCF feedstocks, and applicable production pathways are limiting.

Aviation and maritime sectors

In the short term, demand for sustainable aviation fuel (SAF), which are LCFs used to power aircraft, is most likely to be met by biofuels produced from used cooking oil. However, the supply of this oil is limited and unlikely to increase significantly, which limits the potential of this option to satisfy demand levels. Furthermore, these types of fuels are likely to be subject to a cap under the UK Government's proposed SAF mandate mechanism. Therefore, alternative options, in particular RFNBOs, are preferred in the medium to long term. The potential for RFNBOs is dictated by the availability of renewable electricity capacity, green hydrogen production infrastructure and economic CO_2 availability on-site.

Green ammonia and green methanol are leading LCF candidates for the decarbonisation of the maritime sector, where zero-emission options are not feasible. These LCFs are both RFNBOs produced from green hydrogen. A consensus appears to indicate that ammonia will play the most prominent role, although several benefits to using green methanol were identified.

The UK Government's renewable transport fuel obligation is the major policy mechanism that facilitates the deployment of LCFs in the UK. Over the coming years, this will be supported by the introduction of a SAF mandate, which is planned to require that 10% of aviation fuel supplied in 2030 to be sustainable. The development of the SAF industry in the UK is also being facilitated by programmes such as the Advanced Fuel Fund. Our review of policy relating to decarbonisation of the maritime sector shows that it is less prescriptive than aviation, with the path towards deployment of LCFs being less clear.

1.2 Conclusions

LCFs in Scotland will be essential in decarbonising the aviation and maritime sectors. They will also be used as a complementary pathway to electrification, in the immediate decarbonisation of the long distance road transport fleet prior to full electrification and potentially some other niche sectors. No single feedstock or production pathway can address this issue. Successful deployment of LCF will require a concerted effort across government with a clear understanding that different technologies, feedstocks and economic considerations will be required. Particular sensitivities are development of green hydrogen and carbon capture infrastructure in Scotland.

In the short term, the reliance is likely to be on established biofuel-based technology to meet the demand. The key issue is maintaining a sustainable feedstock as demand increases both domestically from the heat/power sector and from the global economy.

Longer term, the demand would ideally be met by RFNBO-based technology, as this does not generally have the same constraints surrounding feedstock availability as biofuels or RCFs. However, research and investment into the required technology and infrastructure will be essential in realising this potential.

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2 Introduction

Scotland's climate change legislation has set a target of net zero greenhouse gas (GHG) emissions by 2045 [1], which means that net GHG emissions must be equal to zero (or less) by then.

Transport is a significant contributor to Scotland's net GHG emissions. In 2019, the domestic transport sector was the biggest single source, responsible for 25% (12 $MtCO_2e$) of the total net GHG emissions [2], with international aviation and shipping responsible for a further 4% (1.9 $MtCO_2e$) [2]. Therefore, if Scotland is to meet the 2045 net zero target, net GHG emissions from transport must be reduced significantly.

Scotland's Climate Change Plan proposes the following series of targets towards achieving this goal:

- Phase out the need for new petrol and diesel cars and vans by 2030.
- Phase out the need for new petrol and diesel light commercial vehicles by 2025.
- Reduce car kilometres by 20% by 2030.
- Continue work to establish a zero emissions heavy duty vehicle programme.
- Decarbonise scheduled flights within Scotland by 2040.
- Create the world's first zero emission aviation region in partnership with Highlands and Islands Airports.
- Decarbonise Scotland's passenger rail services by 2035.
- Ensure 30% of ferries in Scottish government ownership are low emission by 2032.

In addition to domestic policy, the international aviation and maritime sectors will be governed by international legislation and targets.

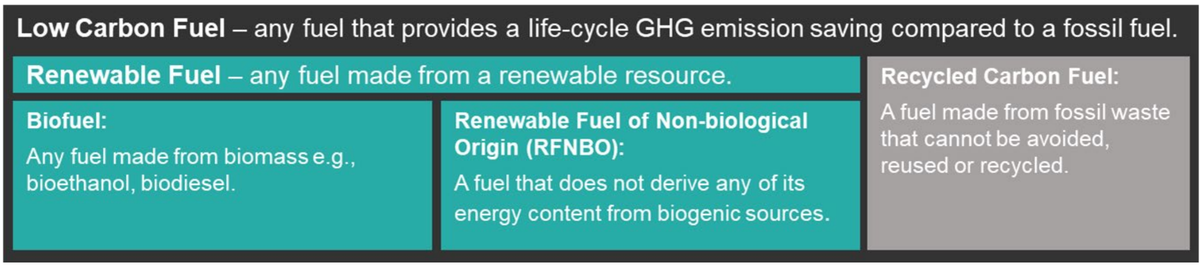
Transport Scotland have articulated a preference towards "zero-tailpipe" emissions solutions in achieving net zero. Zero-tailpipe emissions means that no GHGs are emitted from the vehicle's onboard source of power and include battery electric vehicles (BEVs); fuel-cell electric vehicles (FCEVs); and grid-connected vehicles such as trains and trams. These are zero-emission, provided renewable electricity sources (e.g., wind or solar) are used to charge the battery, produce the hydrogen fuel, or power the grid, respectively.

However, not all transport modes are suitable for electrification using current technologies. The main barriers to the deployment of electrification solutions in decarbonising transport are that batteries are large, heavy, and require frequent or relatively long periods charging [3]. For large vehicles that travel long distances and/or have a high energy use (i.e., long-haul goods vehicles, aeroplanes, ships, etc.) BEVs are not currently a viable option. FCEVs have a higher energy storage density than BEVs, which somewhat mitigates the issues above, although the technology is less mature and generally untested commercially [3]. Furthermore, deployment of FCEVs requires a corresponding hydrogen production and supply chain that has not yet been established.

An alternative solution is required for transport modes that are not compatible with zero emissions technologies.

2.1 Low-carbon fuels

Low carbon fuels (LCFs) are an alternative solution to mitigate GHG emissions in difficult to electrify transport sectors. A LCF is a fuel that provides a GHG emission saving compared to fossil fuels on a life-cycle basis. This means that if LCFs are used instead of fossil fuels, GHG emissions will be reduced. However, the reduction in GHG emissions achieved depends on the type of LCF used and its production pathway. The three types of LCF are defined in Figure 1. A list of descriptors are given in Appendix C. Supporting the difficult to electrify transport modes to decarbonise requires an understanding of LCFs and how and where they are most likely to help.



Low Carbon Fuel – any fuel that provides a life-cycle GHG emission saving compared to a fossil fuel.

Renewable Fuel – any fuel made from a renewable resource.

Biofuel: Any fuel made from biomass e.g., bioethanol, biodiesel.

Renewable Fuel of Non-biological Origin (RFNBO): A fuel that does not derive any of its energy content from biogenic sources.

Recycled Carbon Fuel: A fuel made from fossil waste that cannot be avoided, reused or recycled.

Figure 1. Explanation of common low carbon transport fuel terminology

At the simplest level, LCFs are produced by combining a feedstock with a conversion process. For example, a type of biodiesel (“FAME”) can be produced from used cooking oil (UCO) through the “transesterification” process. However, a given feedstock can usually be converted to an LCF via multiple different conversion pathways. For example, UCO can also be used in the “hydrotreatment” process to produce hydrotreated vegetable oil (HVO), another type of biodiesel. Furthermore, a given conversion process is usually compatible with multiple feedstocks, so for example rapeseed oil can also be converted to FAME biodiesel through the “transesterification” process or HVO through the “hydrotreatment” process.

Given the number of permutations of feedstocks, conversion pathways and fuel types, any discussion on LCFs and relative carbon savings can quite quickly become overly complex. A key goal of this report is to simplify this discussion and provide the reader with a foundational knowledge base of the subject that can be applied more generally to support LCF policy development in Scotland.

3 The role of low-carbon fuels in decarbonising transport

3.1 Current use of low-carbon fuels

In the UK, the use of LCFs is mandated by the Renewable Transport Fuel Obligation (RTFO) order[1]. The scheme is operated by the Department for Transport (DfT) and covers fuels in road, aviation, maritime and non-road mobile machinery applications. The RTFO obligates any entity that supplies more than 450,000 litres of fuel in the UK to include a minimum amount of LCF in the fuel they distribute. The 2022 total obligation on suppliers is 13.5% of the total volume of fuel supplied. The obligation is set to rise to 21% from 2032 onwards. The RTFO is the main policy instrument facilitating the deployment of LCFs in the UK at present.

There are two main LCFs that suppliers currently utilise to meet this obligation: FAME (biodiesel) and bioethanol. These LCFs are blended with fossil diesel and fossil gasoline (petrol) road fuels respectively, a market requiring substantial volumes. The most recent RTFO statistics show that of the 400 million litres of renewable fuel supplied so far in 2022 under the RTFO, 47% was biodiesel and 41% was bioethanol [4]. Statistics pertaining specifically to Scotland are not available publicly. The primary use for these fuels is in road transport. There are little/no LCFs currently used in aviation or maritime sectors.

LCFs can be produced in Scotland from domestic or imported feedstocks. Alternatively, finished fuels produced abroad can be imported and either deployed directly or blended with fossil fuel[2]. The latest RTFO statistics suggest that less than 10% of LCFs currently deployed in the UK are produced from feedstocks sourced in the UK [4].

Argent Energy operate a plant near Motherwell with the capacity to produce 70 million litres of FAME biodiesel per year and utilise a variety of feedstocks [5]. For context, this is equivalent to about 37% of the total UK supply according to the RTFO statistics [4]. It is not clear how much of this feedstock is domestically sourced and how much is imported. We assess that it is most likely that the majority of the feedstock is imported. Similarly, it is unclear how much of this fuel is used domestically or how much is exported. There are no major facilities producing bioethanol in Scotland.

To summarise, the use of LCFs is currently mandated in the UK by the RTFO. FAME and bioethanol are the two most widely used LCFs under this scheme, and they are deployed almost exclusively in road transport. LCFs deployed in the UK are not necessarily produced from feedstocks sourced in the UK, or even produced in the UK at all. Scotland currently has significant capacity to produce FAME, courtesy of the Argent Facilities in Motherwell. It is not clear what proportion of the demand for FAME in Scotland is met by the Argent facility.

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[1] A detailed discussion of the RTFO scheme is beyond the scope of this report. Detailed guidance on the scheme can be found here: https://www.gov.uk/government/publications/renewable-transport-fuel-obligation-rtfo-compliance-reporting-and-verification.

[2] As a rule of thumb, it is more economical to import finished fuels than feedstocks because the fuels have a higher energy density (more energy per litre).

3.2 Future demand for LCFs in Scotland

3.2.1 Road Transport

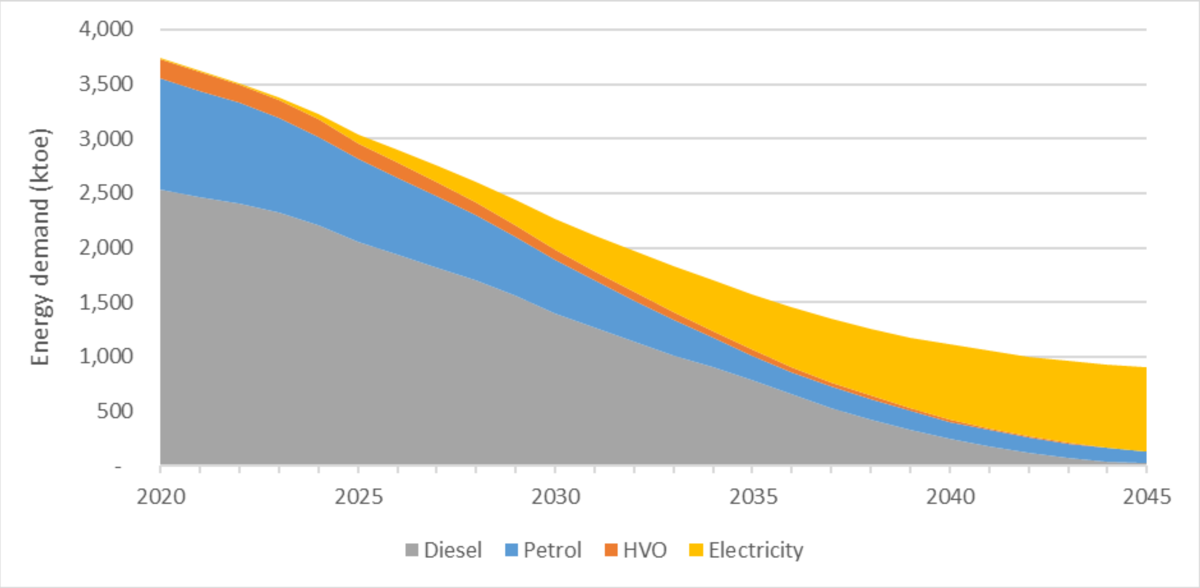

Figure 2 Scotland Road transport energy demand forecast - CCC Net zero pathway

As a greater share of the road transport fleet is electrified, and internal combustion engine (ICE) vehicles are retired from the fleet, the demand for LCFs in road transport will reduce. This is illustrated by Figure 2, using the CCC's Net Zero Pathway for Scotland [6]. Figure 2 shows that the overall demand for energy from road transport is forecast to decline significantly by 2045. Furthermore, the share of total energy demand that is met by diesel, petrol or HVO is also markedly lower in 2045 compared to 2020[3]. There is likely to be minimal demand for LCFs in road transport by 2045 – providing the fleet can be electrified. In the short/medium term however, the current state of play (i.e., use of FAME and bioethanol) is likely to be maintained, where declining ICE numbers brought about by policy intervention are somewhat offset by increased obligations under the RTFO to 2032.

3.2.2 Aviation

The forecast demand for energy from the aviation sector in Scotland according the CCC Net Zero Pathway is shown in Figure 3. Unlike road transport, the demand for energy in aviation is expected to remain roughly constant at current levels to 2050[4]. This is a result of a lack of alternative approaches to reduce the energy demand from aviation compared to road transport through increased efficiency (i.e., electrification) or mass transit.

The overwhelming consensus is that LCFs (known as SAF in the sector), are likely to be essential to decarbonise aviation before 2050. This is reflected in current or upcoming policy, such as the SAF mandate that requires that by 2030 at least 10% of aviation fuel in the UK must be SAF [7]. Equivalent policy (ReFuelEU) is under consideration in the EU [8].

Figure 3 illustrates how the deployment of SAF could develop in Scotland, based on the total energy demand from the CCC's balanced net-zero pathway and the late SAF breakthrough trajectory which is discussed in the SAF Mandate and which also aligns

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[3] Based on current E10 and B7 fuel standards, for each ktoe of biodiesel 0.06 ktoe of biodiesel is needed. For each ktoe of petrol 0.065 ktoe of bioethanol is needed.

[4] The sharp reduction in energy demand around 2020 is a result of the COVID-19 pandemic. Demand is expected to recover to pre-pandemic levels.

with the pathway in ReFuelEU. There are limited options in the choices of LCF that can be deployed in aviation, due to the extreme operating conditions of aeroplanes. Consequently, the pathway to 2050 can be relatively well defined. A significant role is envisaged for biofuels and recycled carbon fuels. This reflects the fact that technology required to produce RFNBOs is nascent therefore only really has an impact from 2040 onwards.

In summary, the future demand for LCF from the aviation sector is relatively well defined. This is a result of the limited options for decarbonising aviation as well as clear policy signals in the UK and EU. There will be a significant demand for SAF internationally (i.e., LCF) in a relative sense from 2022-2030, due to limited supply, and an absolute sense 2030 – 2050.

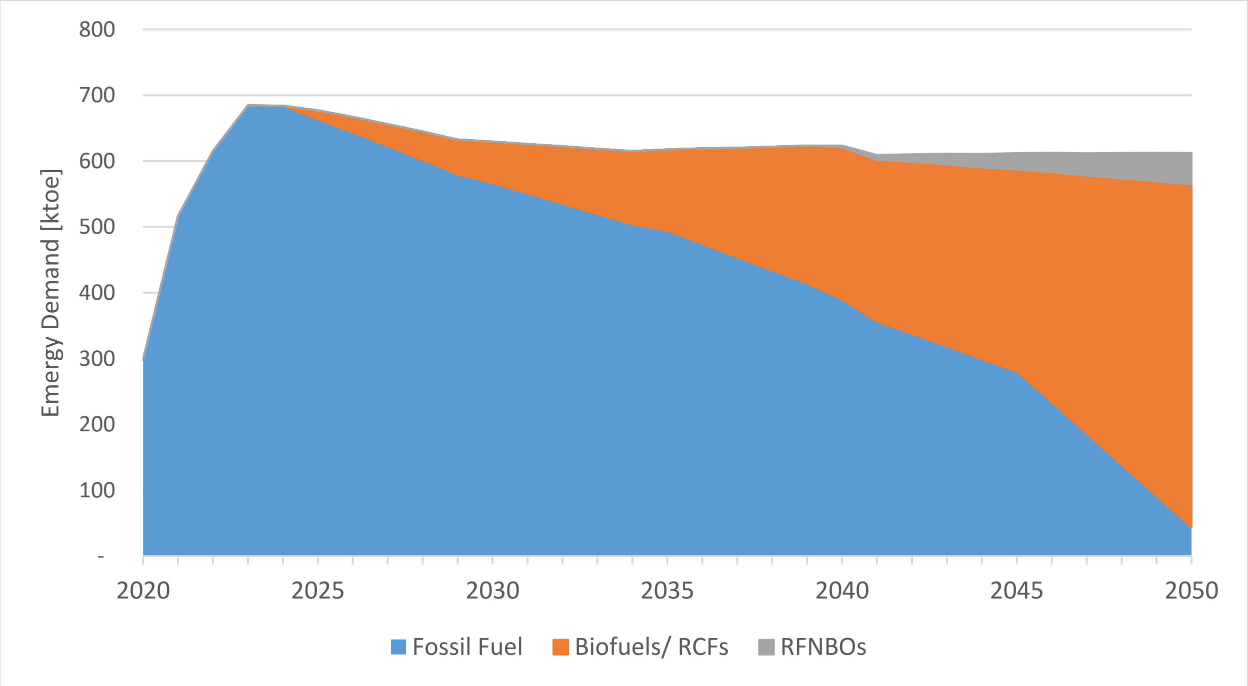

Figure 3 Energy demand scenario from Scottish aviation sector

3.2.3 Maritime

The CCC's 6th Carbon Budget forecasts that the energy demand from the maritime industry in the UK will increase by 1.2% per year from 2020-2050, resulting in a moderate overall increase in energy demand by 2050 as shown in Figure 4. The CCC estimates suggest that only a small portion of this increase demand is likely to be met by electrification. Recent work by Ricardo suggests that zero emission technology, such as fuel cells, is currently too expensive and not robust enough to have a significant impact on maritime emissions by 2050[5]. This indicates that emissions reductions will need to be achieved through improvements in efficiency and the increased use of LCFs.

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[5] The typical lifetime of a ship is 25-35 years. Therefore, mature technology pathways are likely to have the most significant impact because they can be deployed on viable timelines.

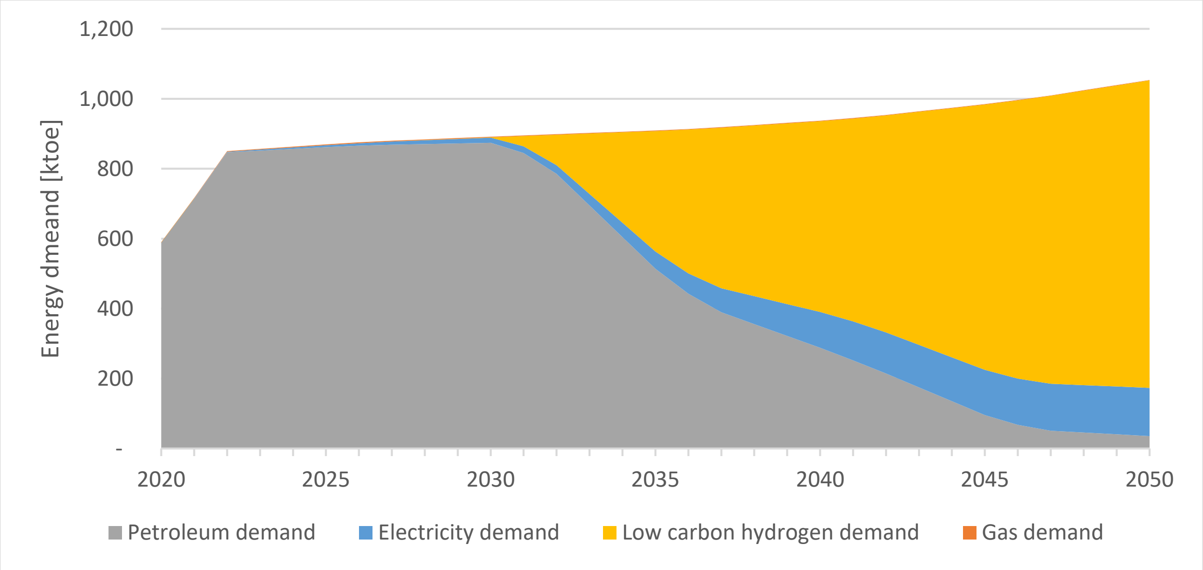

Figure 4 Energy demand scenario from Scottish Maritime sector

A specific trajectory for the deployment of LCFs in the maritime sector is not well defined, and not straightforward to predict. This is because there are few limitations on the types of fuel that can be deployed in the maritime sector, compared to aviation for example. Furthermore, there is uncertainty over the timeframe in which technological options will be ready to be deployed commercially. Finally, there is a range of vessel sizes and applications that also dictate the most viable option for decarbonising.

Nonetheless, there is a general consensus among sources that ammonia will be the major LCF deployed in the maritime sector and that the majority of emissions reductions will be achieved this way [6] [9] [10] [11]. These sources also agree that there is not likely to be significant ammonia deployed before 2030. This is because ammonia production requires a supply of green hydrogen, which will not be available at sufficient scale before then.

Compared to aviation, there is relatively little policy support for the decarbonisation of the maritime sector. DfT have recently closed a consultation on the subject [12], and the FuelEU Maritime proposal is under consideration in the European parliament [13].

It is worth noting that a large ferry manufacturer and operator in Scotland has indicated to Ricardo that following trials of hydrogen ferries, battery and hybrid technologies will be the likely preferred option for shorter and mid-length journeys. This exemplifies a case where the application has dictated the choice of technology.

3.3 Summary

At present, two main LCFs are deployed in the transport sector in Scotland: bioethanol and FAME biodiesel. The deployment of these fuels has been driven predominantly by the RTFO scheme. These LCFs are almost exclusively deployed in road transport. The demand for FAME and bioethanol in road transport is likely to be maintained in the short/medium term but decrease longer term as the road transport fleet is electrified.

The demand for LCFs from the aviation and maritime sectors is likely to increase significantly by 2050. This is because there are limited other options to decarbonise these sectors, so LCFs will play a key role. Deployment of LCF is the aviation sector is clearly incentivised by policy in the UK and EU. Although LCFs are also forecast to play a key role in the decarbonisation of the maritime sector, the path to their deployment is less clear. This is in part due to debates and uncertainties around the best technical option, the range of vessel sizes and uses, and a lack of current policy support.

4 Sustainability of low-carbon fuels

The key consideration around the use of LCFs is sustainability since the ultimate goal of using LCFs is to mitigate CO_2 emissions compared with fossil fuel use. Therefore, it is essential that the any resources that might be used in the production of LCFs, e.g., land, feedstocks, electricity etc, are not replaced by alternatives that are more carbon intensive than if the fossil fuel was used in the first instance. If LCFs are not produced sustainably, the rationale for their use is undermined.

In the UK, the RTFO defines the sustainability criteria that LCFs must comply with in order to be eligible for the scheme. This provides a useful illustration of the key factors that should be considered when assessing sustainability.

4.1 GHG savings and carbon intensity

Under the RTFO, all fuels must meet the greenhouse gas saving criteria. The RTFO stipulates that to be classed as low carbon, a LCF must demonstrate at least 65%[6] greenhouse gas savings compared to a fossil fuel comparator [14].

This comparison is made on the basis of carbon intensity. Carbon intensity is the mass (in grams) of CO_2 equivalent global warming potential[7] (CO_2e) released per megajoule (MJ) of fuel produced i.e., gCO_2e/MJ. The standard value for fossil fuels is 94 gCO_2e/MJ [14]. Therefore, a LCF must have a carbon intensity of less than 32.9 gCO_2e/MJ to be classed as low carbon and eligible for the RTFO.

The carbon intensity of a fuel is dependent on the feedstock and conversion process used to produce the fuel. For example, in the case of bioethanol produced from wheat, the carbon intensity accounts for the emissions from cultivation, drying and storage of the wheat, conversion of the wheat to bioethanol and distribution of the bioethanol to its point of use. The carbon intensity may also consider any emissions that result from land use change as a result crop cultivation.

The methodology to determine the carbon intensity of RCFs is more nuanced than for biofuels and RFNBOs, and subject to an ongoing consultation from DfT [15]. This complexity arises because the carbon intensity must consider the alternative end of life fate of the feedstock i.e., the counterfactual emissions. This is to ensure that use of the feedstock to produce biofuels does not cause indirect emissions elsewhere.

There are often numerous, case specific, variables in the calculation of carbon intensity for a given LCF. Therefore, a detailed discussion of the carbon intensity of various fuel types is of limited utility in the context of this report. Nonetheless, several key trends are worth note[8]:

1. Crop based biofuels tend to have the highest carbon intensity. This is because there are significant emissions associated with crop cultivation e.g., from fertilizer use, land use change (potentially).

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[6] The threshold is 55% if the production facility was operational before 5 October 2015.

[7] CO_2e is a measure of the global warming potential of all of the GHGs emitted during the fuel production process.

[8] This analysis is based on analysis of carbon intensities from the RTFO guidance [14], the BEIS low carbon hydrogen standard [73] and the JEC WtT v5 data set [74].

2. Hydrogen, methanol, and drop-in hydrocarbons produced from renewable electricity (i.e., RFNBOs other than ammonia) tend to have the lowest carbon intensity[9].
3. The carbon intensity of waste-based fuels is mainly dependent on the emissions from the conversion process. Emissions from feedstock production are zero by definition.

4.2 Land use change and biodiversity

The production of feedstocks for biofuels can generate emissions as a result of the change in use of land. Land use change is split into two categories, direct land use change (LUC) and indirect land use change (ILUC). LUC occurs when land that is not used to produce crops is converted to do so, causing changes in the carbon stocks of vegetation and soil. ILUC occurs when a food or feed crop is displaced by LUC, and consequently land is then displaced elsewhere to make up this deficit. The impacts of both LUC and ILUC are most significant when land with high carbon stock is brought into agricultural use. Potential examples for Scotland could be the acquisition of feedstocks through deforestation or through the conversion of peatland to produce feedstocks.

Production of biofuel feedstocks may also offer an opportunity to increase carbon stocks and biodiversity [16]. This can be achieved by reclaiming unused, abandoned, or degraded land for biofuel production. A potential example of this for Scotland would be in the reclamation of land for the production of perennial energy crops. However, for this approach to be successful, clear definitions are needed for exactly what constitutes unused, abandoned, or degraded land.

4.3 The crop cap

The most common concern raised around the use of crops to produce biofuels is the food versus fuel debate, which argues that increased demand for annual crops for biofuel production will have an adverse effect on the global food market [17]. A detailed discussion of this topic is beyond the scope of this report.

As a result of this concern, biofuels produced from annual crops are generally subject to a “crop cap”. In the UK, the RTFO guidance stipulates that crop-derived biofuels are allowed to meet a supplier’s obligation up to a maximum limit of 3.83% in 2021, declining to 2% by 2032 [18]. Similarly, crop-based biofuels are limited in the EU by the renewable energy directive. [19]. Crop-based fuels are completely ineligible under the UKs Sustainable Aviation Fuel Mandate [20]. Biofuels produced from crops are likely to play diminishing role into the future.

4.4 Feedstock competing use

Many of the feedstocks that are needed to produce LCFs for transport can also be used to decarbonise heat/power generation. Therefore, there will be competition for these resources both domestically and internationally. In the case of biofuels and RCFs, there is direct competition for the feedstocks. For example, lignocellulosic feedstocks are essential for Scotland to meet its bioenergy carbon capture and storage (BECCS) ambitions [21] and residual waste is used extensively in energy from waste facilities. In the case of RFNBOs, the competition is for green renewable electricity.

In the case of renewable electricity for RFNBO production, competing use is mitigated by stipulating additionality requirements [22]. To meet the additionality requirements, the

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[9] Providing the renewable electricity meets additionality requirements.

fuel producer must be able to show that the renewable electricity is considered additional. This means that it either would not have been produced or would have been wasted if not for RFNBO production.

4.5 Summary

The points outlined in this section provide an overview of the general considerations that might dictate whether or not the use of a particular LCF should be encouraged and to provide essential context for the following discussion. The key points are:

- Fuels must have a carbon intensity sufficiently lower than fossil fuels to be considered low carbon.
- The carbon intensity of an LCF depends on the feedstock *and* conversion technology used in its production.
- Land use change (that has a carbon cost) must be avoided.
- The conversion of agricultural land to produce biofuel crops should not be encouraged.
- Renewable electricity (for RFNBO production) must be additional.
- There will be competition for limited resources from other sectors of the economy than transport.

5 Feedstocks for low-carbon fuels

5.1 Feedstocks for biofuels

In this report, we have grouped biofuel feedstocks according to their common “chemical” structure/properties. This grouping is helpful because feedstocks within a given category are generally all compatible with the same conversion processes, somewhat simplifying the discussion.

5.1.1 Lipid Feedstocks

Lipid feedstocks are the most common feedstocks used to produce biofuels at present. Currently, they are used most commonly to produce FAME. Lipids are either derived from crops, waste oils or animal fats.

Crop derived lipids are subject to the considerations regarding fuel versus food and land use change. In the UK, no oil crops are currently grown to produce transport fuels [23] and none of the FAME used in the UK is produced from oil crops, according to the RTFO [4]. Globally, palm oil fruit, soybeans and oilseed rape are the most common lipid crops and are used to produce most of the FAME consumed in the EU [24].

Waste lipids are a significant feedstock for biofuels. According to the most recent RTFO statistics, 93% of biodiesel used in the UK was produced from used cooking oil (UCO). In the future, UCO is also likely to be an important feedstock for the production of sustainable aviation fuel (see Section 6.2). Demand for UCO derived biofuels is likely to increase significantly both domestically and globally [25].

It is unlikely that the domestic supply (Scotland and the UK in general) of UCO will increase significantly. UCO is obtained from either commercial kitchens or domestic households. The majority of UCO generated commercially is currently collected, and there is limited potential for increased in collection from households [25]. Any increase in demand for UCO will likely need to be met by imports.

A significant risk associated with the use of UCO as a feedstock is that its supply is geographically concentrated to a limited number of countries – most notably China. We estimate that around a third of the UCO available globally is generated in China. Furthermore, China does not currently have any policy that incentivises the use of biodiesel domestically, so there are few disincentives to export UCO. If this were to change, there is likely to be a significant impact on the availability of UCO on the global market. Such a change in policy has recently been enacted by Indonesia, another major exporter of UCO [26], where severe restrictions have been placed on the export of UCO [27].

Animal fats, such as tallow, are also viable waste lipid feedstocks for the production of transport fuels. There are a number of facilities that produce tallow located in Scotland [28]. Tallow is one of the most significant bioenergy resources in Scotland [21].

Animal fats are categorised as category 1,2 or 3 depending on how hazardous they are [29]. Category 3 animal fats have competing uses in pet food and cosmetics, therefore, are not permissible feedstocks under the RTFO. Categories 1 and 2 tallow can be used as a biofuel feedstock. As with UCO, domestic supply is limited and not likely to expand significantly. Furthermore, following Brexit the export of tallow from the EU to the UK is prohibited further reducing the available supply. Internationally, the USA and Australia are major producers of tallow.

5.1.2 Sugar and Starch Feedstocks

Sugars and starches are among the most common feedstocks used to produced biofuels at present. The most common source of sugar and starch feedstocks are crops. In the UK, wheat and sugar beet are those most commonly grown [23], and used to produce bioethanol domestically. There are no bioethanol production facilities in Scotland. Furthermore, it is not likely that the supply of sugar beet or wheat for biofuels in the UK will increase due to the crop cap.

According to the latest RTFO report, 66% of the bioethanol consumed as transport fuel in the UK in 2022 was produced using corn from Ukraine and the USA [4]. It is likely this was imported to the UK as ethanol, rather than corn.

5.1.3 Lignocellulosic Feedstocks

Lignocellulosic is an umbrella term for feedstocks comprised of dry biogenic matter. It is an extremely broad classification. Here, we have summarised the most relevant examples for Scotland.

Perennial Energy Crops

Perennial energy crops are a major potential lignocellulosic feedstock. Perennial energy crops are grown specifically for energy purposes and cannot be used as food or feed. They are also generally robust and can therefore be grown on low-grade agricultural or marginal lands, limiting the displacement of food and feed crops. These two factors mitigate many of the disadvantages associated with annual crops described above. The most commonly considered perennial energy crops are short rotation coppice (SRC) tree plantations and miscanthus [30]. SRC is more generally suited to Scotland due to its higher tolerance of frost.

A recent report outlines in detail the potential for perennial energy crops in Scotland [30]. The report highlights that the land available for their cultivations ranges between 70,000 and 250,000 ha. Additionally, the amount of perennial energy crops available is highly dependent on the rate at which any available land is planted. Therefore, there is significant uncertainty surrounding the quantity and quality of perennial energy crops that could theoretically be produced in Scotland, and the timeline over which they are likely to be available.

Perennial energy crops are not currently used in Scotland to produce transport fuels. A small quantity of short rotation coppice (SRC) is grown in Scotland but is used to produce heat/power [30]. Availability of perennial energy crops to produce biofuels is possible but will take time. Miscanthus requires 2-3 years to mature, while SRC require 4-5 years to be ready for harvest. Therefore, domestically produced perennial energy crops are only likely to be available 2025-2030. The situation is similar for short rotation forestry, which takes over 10 years to cultivate.

Forestry Waste and Residues

Several products of forestry industry can be used as lignocellulosic feedstocks for the production of transport fuels. These are small roundwood (SRW), forestry thinnings, sawmill residues and arboricultural arisings. The availability of these feedstocks is driven by the harvesting and processing of saw logs, and demand for small round wood (SRW) and sawmill residues in other markets [21]. Availability of these resources is not expected to change significantly before 2030 as a result of the maturation time of conventional forests [21].

At present, all of the available SRW, sawmill residues and arboricultural arisings produced in Scotland are used to generate heat/power, but available forestry thinnings are currently not fully utilised [21][10]. Out of these feedstocks, only the availability of sawmill residues is expected to significantly increase by 2030 [21]. Therefore, it is unlikely that significant quantities of forestry wastes and residues will be available for the production of biofuels in Scotland if current BECCs ambitions are to be met.

Other Lignocellulosic Wastes and Residues

Straw is produced as a by-product of cereal crop farming. The primary uses for straw are as animal bedding, or re-ploughing back into land. There is a small quantity of straw that is not needed for either of these uses and is available for bioenergy. In Scotland, all available straw is used to generate heat/power. The total quantity of straw available for bioenergy in Scotland is not expected to change significantly by 2030 [21]. Therefore, it is not likely that straw will be a significant feedstock for the production of biofuels in Scotland.

Similarly, waste wood is a lignocellulosic feedstock that could be used to produce transport fuels. However, the current waste wood supply in Scotland is utilised for other bioenergy purposes and the supply is not expected to increase significantly [21].

5.1.4 High water content feedstocks

Some common feedstocks for biofuel production are best characterised by their high water content. These are manure, sewage sludge, food waste, draff and pot ale syrup. A common feature of these feedstocks is that it is not economical to transport them large distances (due to their high weight relative to value). The high water content of these feedstocks means that most of the volume being transported is water – which has no energetic value. Consequently, these feedstocks are most often used close to where they are produced and are not suitable for import/export.

5.2 Feedstocks for recycled carbon fuels

Recycled carbon fuels (RCF) are fuels made from fossil hydrocarbon waste that cannot be avoided, reused or recycled. According to the waste hierarchy, energy recovery (e.g., conversion to a fuel or heat/power[11]) is the next most preferable end-of-life fate for fossil waste. All these end-of-life fates are preferable to landfill.

The GHG savings delivered by RCFs are dependent on three factors [31]:

1. Emissions that no longer occur when the feedstock is diverted from its existing end of life fate.
2. Emissions that are generated due to the displacement of the feedstock from its current end of life fate.
3. Emissions that no longer occur due to the displacement of a primary fossil fuel by a RCF.

Generally, the emissions associated with RCF use are lowest when the feedstock would have been combusted anyway or it was not used to produce useful heat/power. If the

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[10] Leaving forestry residues in situ can be beneficial to the health of the forest.

[11] There is currently ongoing debate as to whether fuel production should be placed above heat/power generation in the waste hierarchy, given that renewables can be used to generate heat/power. Currently, the waste hierarchy is constructed to ensure that waste is managed appropriately and is technology agnostic.

feedstock was used to produced heat/power, this must be replaced by a low carbon alternative [31].

RCF feedstocks are not currently supported under the RTFO. This is because they are of fossil origin and cannot be classed as renewable. DfT have recently concluded a series of consultations on supporting RCFs under the RTFO. DfT are proposing to support industry waste gases and RCFs made from refuse derived fuel (RDF) under the RTFO. Other fossil waste feedstocks such as end-of-life tyres are viable options for the production of RCF but are not currently under consideration as feedstocks under the RTFO [15].

5.2.1 Industry waste gases

The term industry waste gas generally refers to integrated steel mill, ferro-alloy, and refinery off-gases. The most active route to fuel production from industry waste gases is through fermentation of steel mill waste gases to ethanol [32]. More specialised routes can also produce methanol and ammonia [33].

Transportation of industry waste gases is challenging and generally not viable. Therefore, this feedstock is most likely to be used at the site of production. There are no integrated steel mills[12] or ferro-alloy plants in Scotland. The only oil refinery in Scotland is the Petroineos facility, located at Grangemouth [34].

In the context of a refinery, waste gas refers to the gaseous products generated within the normal operation of a refinery (processing of crude oil) that cannot be isolated and sold. Typically, this gas is used within the refinery to generate heat/power [31]. A less common end of life fate of refinery waste gases is flaring [35]. Displaced refinery waste gases are most likely to be replaced by natural gas to generate heat/power in the refinery [31]. On this basis, recent analysis by E4tech suggests that diversion of refinery waste gases to produce transport fuels is unlikely to produce GHG emissions savings [31].

5.2.2 Residual waste

Residual waste is waste generated in the municipal or non-hazardous commercial and industrial waste streams. It cannot be prevented or reused and has not been recovered in the recycled waste stream. Residual waste therefore contains both fossil and biogenic components. This residual waste stream is used to produce refuse derived fuel (RDF). RDF is produced by the mechanical treatment of residual waste, to remove any non-combustible materials. Following this process, it is shredded.

The availability of residual waste is highly sensitive to waste management policies. By 2025 Scotland has the following targets for all waste [36]:

- Reduce total waste arisings by 15% compared to 2011 levels.
- Recycle 70% of remaining waste.
- Send no more than 5% of residual waste to landfill.

Reducing total waste arisings and increasing the recycling rate will both lead to a reduction available residual waste. Diverting waste from landfill could present an opportunity for Energy from Waste (EfW) plants and also reduce available residual waste. For context, in 2021, 26% of household waste[13] was landfilled [37]. Clearly, if the proposed targets are met, the amount of available residual waste will reduce significantly from current levels. Analysis carried out by Ricardo suggests that these policies could

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[12] Waste gases are only generated by integrated steel mills that use blast furnaces. Waste gases are not generated by electric arc furnaces.

[13] Data on the availability of commercial waste is generally not publicly available.

lead to a reduction in residual waste of around 50% by 2050 [38]. Therefore, caution must be taken when considering developing LCF policy around residual waste.

Residual household waste is currently most often used to generate heat and power in energy from waste (EfW) facilities. There are 6 EfW facilities operational in Scotland that utilise residual waste [39]. Therefore, RCF production would be in direct competition with EfW facilities for residual waste as a feedstock. EfW facilities generally have long term contracts with waste management companies. This means that even though residual waste is being generated, it is not necessarily available on the market.

Facilities that use residual waste as a feedstock charge a gate fee to receive residual waste. This is a major revenue stream for these plants. Given that EfW facilities are already well established and have long contracts, they will likely achieve capital recovery well in advance of any potential RCF production facility and will be in a financial position to offer lower gate fees. This could harm the economic competitiveness of RCF production, from the perspective of the feedstock suppliers.

5.3 Feedstocks for RFNBOs

Renewable fuels of non-biological origin (RFNBO) are renewable fuels that do not derive any of their energy content from biogenic sources [40]. The energy content of RFNBOs must be derived from non-biogenic renewable energy sources e.g., wind, solar etc. This also means that any additional feedstocks used to produce RFNBOs must not contain any useable energy. i.e., RFNBOs can only be produced using renewable electricity, CO_2, nitrogen or water. Nitrogen has not been considered as a feedstock in the discussion below because it is abundant in air, which is 78% nitrogen.

5.3.1 Additional renewable electricity and hydrogen

Hydrogen is the simplest RFNBO. Renewable electricity converts water to “green” hydrogen (as well as oxygen – which is generally vented to atmosphere), through a process called electrolysis. Hydrogen can also be used as a feedstock to produce drop-in RFNBOs (see Appendix B).

Scotland’s potential renewable electricity supply is a major asset in this regard. This is reflected in ambitious targets for hydrogen production [41]. If these targets are met, availability of renewable electricity/hydrogen is likely to be the least constraining factor in regard to RFNBO production.

5.3.2 Carbon dioxide

CO_2 is a key feedstock for the production of RFNBOs. According to current RTFO rules, CO_2 for RFNBO production must not be generated specifically for the that purpose [40]. Therefore, there are two main sources of CO_2; point sources and direct air capture (DAC).

Point source CO_2 is captured from single “point sources” for example power stations or refineries. SEPA maintains an inventory of major point sources in Scotland, which are numerous [42]. The two most significant sources are the SSE gas power station at Peterhead and the Petroineos facility at Grangemouth. SSE have outlined plans to install carbon capture capacity of up to 1.5 million tonnes at the Peterhead site by 2030 [43]. Similarly, Ineos have entered into a *Memorandum of Understanding* to develop 1 million tonnes of carbon capture capacity at the Grangemouth site by 2027 [44]. This suggests that although point source CO_2 will be abundant in Scotland towards 2030, potential for RFNBO production is likely to be limited before then.

Direct air capture (DAC) extracts CO_2 directly from the air. There are two commercially developed approaches that can achieve this, solid sorbent DAC and liquid solvent DAC

[45]. The energy demands of both these systems are comparable, however solid sorbent systems require much lower grade thermal energy which can be met by waste industrial heat [45].

This technology is relatively immature and is yet to be proven at scale. Storegga, in collaboration with Carbon Engineering, have proposed to develop a large-scale DAC facility in North-East Scotland which would be the biggest demonstration to date in Europe [46].

DAC facilities require large quantities of power, either from natural gas or electricity, and water to operate [47]. It is likely that these factors will change over time as DAC technology matures. Therefore, the impact of the largescale deployment of DAC needs careful consideration. Going forward it is important to maintain a firm understanding of the lifecycle emissions of DAC facilities.

DAC is significantly more expensive than point source CO_2. This is mainly because the concentration of CO_2 in the air is much lower than at point sources. Therefore, DAC is unlikely to be an economically competitive option in the near to mid-term so long as point-source CO_2 is abundant. An increased carbon price would most likely improve the economic viability of DAC.

Concawe have reported that the CO_2 abatement potential of RFNBOs produced from point source and DAC are similar [48]. However, others have argued that only DAC CO_2 is truly carbon neutral [49]. CO_2 will always be emitted when a RFNBO is combusted. However, in the case of DAC, this CO_2 is part of a closed cycle and can be removed from the atmosphere. For point sources, combustion of the RFNBO will lead to a net increase of atmospheric CO_2.

6 Production of low-carbon fuels

For clarity, this report has focused on the most likely LCF production routes based on the expected demand for LCFs in Scotland discussed in Section 3.2. A comprehensive schematic overview of LCF production routes is available in Appendix D.

6.1 Low-carbon fuels for road transport20

The overwhelming trend in road transport is towards electrification. Consequently, it is unlikely that we will see a significant shift in the LCFs deployed in road transport i.e., bioethanol and FAME are likely to continue to be widely used in road transport.

6.1.1 Bioethanol

Bioethanol from sugar and starch crops is currently the second most used LCF in the UK [50]. Current fuel standards allow ethanol to be blended with petrol up to a *maximum* of 10% by volume. This is known as "E10" petrol. However, petrol can contain 0% ethanol and still be labelled as E10. i.e., fuel standards *permit* blending of biofuels up to 10% but do not *mandate* it. The 2021 RTFO statistics suggest that the average blending rate of ethanol in petrol in the UK is about 6%. The RTFO is the mechanism by which the LCF content of fuels is increased.

Sugar and starch feedstocks are converted to bioethanol by fermentation. The cost of bioethanol production is largely driven by the feedstock cost [51]. This technology is widely deployed commercially. The main drawback to this pathway is that crops are the main feedstock, and the market is therefore limited by the crop cap.

Bioethanol ("lignocellulosic ethanol") can also be produced from the fermentation of lignocellulosic feedstocks. Lignocellulosic ethanol is not subject to any crop caps. However, lignocellulosic feedstocks require more processing than crops before they can be converted to ethanol. This means that lignocellulosic ethanol is more expensive than bioethanol produced from crops. Lignocellulosic ethanol production costs are 0.75-0.80 €/litre while crop based ethanol costs around 0.45 €/litre [52]. These costs are anticipated to decrease over time.

6.1.2 FAME

FAME (fatty acid methyl ester) is an LCF that can be blended with diesel fuel and is the most used LCF in the UK, according to the RTFO Statistics [50]. It is produced by a process called "transesterification". Transesterification can use any lipid (i.e. fats/oils) as a feedstock. Examples of commonly used feedstocks are vegetable oil, palm oil, used cooking oil (UCO) and animal fat (tallow).

FAME is most often used in road transport but cannot generally be blended with diesel past a certain volume[14], as it is not compatible with typical engines (see Appendix C). It can also be blended with marine fuel, but this is not frequently done. It is not compatible with petrol or kerosene. FAME cannot be upgraded to more diverse fuel products. Therefore, use of lipids in transesterification generally consigns them for use in the diesel market.

6.1.3 HVO

Any feedstock that can be used to produce FAME can also be used to produce HVO (hydrotreated vegetable oil), *via* hydrotreatment. The main advantage to using HVO over FAME is that HVO is a "drop-in" diesel fuel, therefore there is no limit on how much can be blended with standard fossil-based diesel.

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[14] At the moment this limit is 7%.

The capex required to develop an hydrotreatment plant is typically higher than that needed for a FAME plant [53]. Similarly, production costs are higher. However, this may be offset to some extent by the higher price commanded for the hydrotreatment products as a result of their more desirable properties as a fuel compared to FAME [53].

6.1.4 Co-processing

Co-processing is an alternative route to processing lipids. The lipid feedstock is blended with crude oil in low volumes (<10%) at a conventional refinery and incorporated into the standard operation of the refinery (with minor modifications). Co-processing produces fossil diesel mixed with HVO.

The advantage of co-processing is that it can be integrated into the existing infrastructure therefore requires low capex and also protects jobs. The disadvantage is that the amount of HVO blended with the final fuel is limited by the fraction of feedstock that can be co-processed [53].

6.1.5 Hydrogen

The production of hydrogen is likely to be key across all transport modes. This is because hydrogen can either be used directly as a fuel for combustion, or in a fuel cell to produce electricity, or as a feedstock to produce other LCFs.

Hydrogen production routes are shown in Table 1. Currently 95% of the world’s hydrogen is produced by steam methane reforming of natural gas [54], which has high carbon emissions and so is not eligible to be used as a feedstock to make LCFs. Biohydrogen and green hydrogen may be used as a fuel directly or in fuel cells. By definition, only green hydrogen can be used to produce RFNBOs under the RTFO [22]. For LCFs derived from hydrogen to be widely deployed, a significant scale up in hydrogen production capacity from these sources is needed.

Table 1. Hydrogen production routes

Fuel	Conversion route	Feedstock	Fuel type
Grey hydrogen (known as blue hydrogen when CCS is used)	Steam methane reforming (+ Carbon capture & storage)	Natural gas	Fossil
Biohydrogen	Gasification + water gas shift	Lignocellulosic biomass	Biofuel
	Steam methane reforming	Biomethane	Biofuel
Green hydrogen	Electrolysis	Renewable electricity and water	RFNBO

The main benefit hydrogen as a fuel is that is does not emit CO_2 when used. Hydrogen also has a superior energy density by weight (energy per kg) to batteries. This makes hydrogen fuel especially suited to heavy vehicle applications such as buses and HGVs. Another benefit of using hydrogen over batteries is that vehicles can be refuelled quickly [55].

However, there are several drawbacks. Firstly, hydrogen produced by electrolysis is currently expensive and costs around 2.5 – 5.0 £/kg to produce[15], although costs are expected to decrease as the technology matures [55]. Secondly, the distribution and refuelling infrastructure required for the wide scale utilisation of hydrogen as a fuel has not been developed. Thirdly, hydrogen has a very low energy density by volume and to store sufficient energy onboard vehicles, it must be highly compressed or liquefied - both energy-intensive processes. Finally, modified vehicle technologies are needed to use hydrogen as a fuel, which are currently expensive and not widely available.

Overall, there is uncertainty over the role hydrogen will play as a transport fuel in Scotland. It is unlikely that the supply of hydrogen will be an issue in Scotland. Development of the distribution infrastructure and deployment of suitable vehicles will be a key determining factor and is in the control of Scottish policy makers. The most likely role for hydrogen is in heavy duty road vehicles [55]. Ultimately however, deployment of hydrogen is likely to depend on the price coming down over time, which will require technological advancements.

6.2 Low-carbon fuels for aviation

Low-carbon fuels in this sector are also known as sustainable aviation fuel (SAF).

Table 2. Approved production routes for sustainable aviation fuels

Fuel	**Conversion route**	**Feedstock (direct emissions gCO_2e/MJ)** [56]	**Blending limit (max volume)**
HEFA	Hydroprocessing	- Lipids (19.4)	50%
FT-SPK	Fisher-Tropsch	- Lignocellulosic (6.3-11.7) - Residual waste (14.8) - Green hydrogen (1)	50%
FT-SPK/A			50%
ATJ	Dehydration & Oligomerisation	- Lignocellulosic (14.9-20.3) - Industry waste gases (19.6)[16]	50%
HH-SPK	Fermentation & hydroprocessing	- Oil produced from algae	10%
CHJ	Hydrothermal liquefaction	- Lipids	50%
HFS-SIP	Fermentation	- Sugar crops (47)	10%

HEFA = Hydroprocessed Esters and Fatty Acids
FT-SPK = Fischer-Tropsch Synthetic Paraffinic Kerosene
FT-SPK/A = FT-SPK with aromatics
ATJ = Alcohol-to-Jet Synthetic Paraffinic Kerosene
HH-SPK = High Hydrogen Content Synthetic Paraffinic Kerosene
CHJ = Catalytic hydrothermolysis synthetic jet fuel
HFS-SIP = Hydroprocessed Fermented Sugars to Synthetic Isoparaffins

LCFs must be tested and certified before they can be used in aviation [57]. This certification ensures that the fuel has similar properties to conventional jet fuel and ensures compatibility with the global fleet and infrastructure i.e., they must be drop-in fuels[17]. Consequently, the options for deploying LCF in aviation are relatively clear.

Only seven LCFs are currently approved for use in aviation (Table 2). Although these LCFs are technically drop-in fuels, they currently have blending limits. These blending limits to guarantee that the fuels remain compatible with all aircraft, they are not a technical hard limit. Trials are ongoing to test and validate aircraft operation using 100%

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[15] Note that retail prices are significantly higher
[16] https://www.energy.gov/sites/default/files/2017/07/f35/BETO_2017WTE-Workshop_SeanSimpson-LanzaTech.pdf
[17] See Appendix C for definition of drop-in fuel

SAF [58]. An advantage of this is that adoption of SAF does not necessitate a turnover of the fleet.

There are currently no operational or planned SAF production facilities in Scotland.

HEFA (Hydroprocessed Esters and Fatty Acids) is often identified as the most viable option in the short term [7]. This is because this production route is the cheapest and most well developed commercially [7]. The process to produce HEFA is very similar to the HVO process. In fact, both HEFA and HVO are usually produced at the same time. A facility producing HVO will produce ~25% HEFA as a co-product [56]. HEFA can be produced from UCO for around €0.9 per litre [56], which is around twice as expensive than fossil jet fuel [56].

However, the amount of HEFA eligible to be used in the UK under the SAF mandate will be capped. This is to ensure that the anticipated significant demand for HEFA from aviation does not draw feedstocks from other uses (i.e., FAME or HVO) [7]. A similar cap is proposed at EU level [8]. Therefore, HEFA is not scalable over time, and other options are required.

Although currently more expensive, research has shown that FT-SPK (Fischer-Tropsch Synthetic Paraffinic Kerosene) may eventually be cost competitive with HEFA and has a lower carbon intensity [7]. Currently, it is estimated that FT-SPK produced from green hydrogen and CO_2 would cost €2.4 per litre. However, around 70% of this levelised cost is renewable electricity. Therefore, there may be potential to lower this significantly in Scotland if cheap renewable electricity is available.

FT-pathways can use a range of feedstocks and the overall carbon intensity depends on the exact configuration implemented. FT-SPK from green hydrogen and CO_2 is a particularly attractive option as this route is not as constrained by feedstock availability long term compared to other options. However, this route is likely to be a longer-term option as the technology for both green H_2 production and CO_2 capture is less well developed. The SAF mandate has a minimum target that covers fuels produced from green hydrogen to incentivise their development in the short term [7].

Alternative feedstocks for FT-SPK are residual waste, or lignocellulosic materials. The availability of residual waste in Scotland is limited therefore it is not likely to play a significant role as a feedstock. It is difficult to assess the potential for FT-SPK from lignocellulosic feedstocks in Scotland. This is because currently available lignocellulosic materials (e.g., forestry wastes and residues) are mainly needed to meet Scotland’s BECCS ambitions and the only other major source of lignocellulosic material, perennial energy crops, are not eligible under the SAF mandate.

ATJ is not likely to be a viable option for production in Scotland due to the absence of suitable industry (steel mill) waste gas sources. Comparison of the direct emissions for each process suggests that lignocellulosic feedstocks may be better deployed in FT-SPK routes (Table 2), which are also generally cheaper [7].

The remaining approved SAFs are produced using relatively new pathways and are currently quite niche. It is difficult to assess at this stage what role they may play.

Even the cheapest SAF is significantly more expensive than fossil jet fuel. Policy intervention, for example the SAF mandate, is essential to ensure uptake.

The above discussion suggests that in the short-medium term, Scotland is likely to be highly dependent on imports of SAF, either from elsewhere in the UK or internationally. This conclusion is based on the fact that there are no plans to produce SAF in Scotland, and that our assessment suggests a lack of availability of appropriate feedstocks.

6.3 Low-carbon fuels for maritime

As discussed above in Section 3.2.3, the general consensus appears to be that ammonia will be the LCF most widely deployed in the maritime sector. Ammonia can be considered a “hydrogen carrier”. This means that it offers the same benefit as hydrogen (no CO_2 emissions) but is easily liquified – therefore, is much easier to handle (though toxic). Green ammonia can achieve GHG reductions of up to 90% compared to fossil fuels [11].

Ammonia is produced using green hydrogen and air through the Haber-Bosch process. This process is already deployed commercially at large scales to produce fertiliser using grey hydrogen, so there are minimal technology risks associated with its production. However, maritime vessels would require modification to utilise ammonia as a fuel. Furthermore, there is currently no bunkering infrastructure for ammonia in place, and no known efforts to install ammonia supplied as a fuel in ports [11].

A commercial green ammonia plant is planned for Orkney [59]. This site has been chosen as it is co-located with green hydrogen production.

Green methanol is also being adopted in the shipping industry [60]. Green methanol is produced from green hydrogen and CO_2 (from either point source or direct air capture). Green methanol can offer GHG savings comparable to green ammonia [11]. Furthermore, 88 of the world’s top 100 ports are equipped with the infrastructure to store and handle methanol as a fuel [61].

7 Low-carbon fuel policy

7.1 UK policy

A number of measures have been put in place by the UK government to facilitate the deployment of LCFs.

7.1.1 RTFO Scheme

As discussed in Section 3.1, current demand for LCFs in the UK is driven by the RTFO. The RTFO places the obligation on the fuel supplier to distribute a minimum quantity of eligible LCFs in their fuel. The obligation can be met either by claiming a renewable transport fuel certificate (RTFC) for supplying an eligible fuel, buying certificates from another supplier, or by paying a fixed sum to buy out their obligation. Suppliers can obtain an RTFC per litre of eligible fuel produced. RTFCs can then be traded, and the price is driven by the market. The total obligation is set to rise from 13.5% in 2022, to 21.1% in 2032.

The RTFO also contains a “development fuel” obligation. Development fuels can either be LCFs produced from a specified feedstock i.e., a waste or residue[18], or a specific fuel type e.g., hydrogen. Development fuels are eligible for two RTFCs. The development fuel obligation is designed to incentivise the deployment of strategically important feedstocks or fuels.

7.1.2 Jet Zero Strategy

In July 2022 the UK government announced its Jet Zero Strategy [62]. This has the overall goal of achieving net zero emissions from aviation by 2050. In the interim, emissions must be reduced by 7.3% in 2030 and 26% in 2040, compared to 2019 levels. SAF is seen as the key lever to accelerate the transition to net zero. There are two key actions to facilitate the deployment of SAF: the SAF mandate and the advanced fuels fund.

7.1.3 SAF Mandate

The SAF mandate will be introduced in 2025 and mandate that by 2030 at least 10% of the aviation fuel supplied in the UK must be SAF [20]. The mandate will be based on GHG savings, rather than a blending volume. Therefore, suppliers will be able to blend lower volumes of SAF that have a higher GHG saving. The 10% target is based on an assumed GHG saving of 75% [20].

For biofuels to count towards the supplier’s obligation they must be produced from wastes and residues (i.e., no crops) and will need to show GHG savings of 50% compared to a fossil fuel comparator of 89 gCO_2e/MJ[19].

The Government intends to introduce a cap on the contribution that HEFA from UCO and tallow can make to the obligated fuel volume. It is undecided yet how this cap would be applied and whether it would apply to the total volume of SAF that could come from UCO/tallow based HEFA and/or to the contribution that it could make to the GHG savings requirement. As well as a HEFA cap, the Government intends to introduce a sub-target for RFNBOs in the mandate.

7.1.4 Advanced Fuels Fund

The advanced fuels fund will provide up to £165 million in funding to support the development of the SAF industry in the UK. The key objectives of the Advanced Fuels Fund are to:

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[18] Although it is a waste, UCO and tallow are not eligible as development fuel feedstocks.

[19] i.e., it will need to have a maximum carbon intensity of 44.5 gCO_2e/MJ.

- Kickstart the UK advanced fuels sector with the commercial deployment of innovative fuel production technologies that are capable of significantly reducing near-term UK aviation emissions.
- Broaden and strengthen the UK project pipeline, getting as many UK projects as possible to an "investment ready" state.
- Support the advancement of a diverse range of technology routes to SAF and other advanced fuels.

LCFs produced using UCO/tallow are not eligible for the fund. A sub-pot of £22 million has been allocated to RFNBOs.

7.1.5 UK maritime decarbonisation policy

The UK government published the “Clean Maritime Plan” in 2019 that set out its roadmap to decarbonisation of the maritime industry [63]. This included some ambitions but no clear timings for widespread uptake of alternative fuels. The document announced research into biofuels for shipping but also noted the Committee for Climate Change’s advice that biofuels should be directed towards the hardest to abate sectors.

7.2 Scottish policy

The draft Energy Strategy and Just Transition Plan provides some clarity on the role of LCFs in decarbonising transport in Scotland. It states that any support for low-emission fuels would be dependent on evidence that use of low-emission technology would not lead to a delay in achieving fully zero-emission transport [64]. The approach to date has been dictated by the RTFO [65] and is likely to continue to be so.

7.2.1 Bioenergy Action Plan

The Bioenergy Action Plan will consider how best to manage the production and use of crops and other biomass resources for biofuels and other uses in Scotland, as well as policy on future energy from waste facilities. Both of these developments will impact the potential feedstocks available for biofuel and RCF production in Scotland.

7.2.2 Hydrogen Action Plan

The Scottish government’s Hydrogen Action Plan published in December 2022, provides an overview of action which will be taken to support the hydrogen economy [66]. The target is to achieve 5 GW of Hydrogen production by 2030, increasing to 25 GW by 2045. Increasing the supply of hydrogen seeks to support emissions reductions across the energy system, homes, industry as well as transport, while ensuring a just transition.

Funding is central to the Plan, with £100m committed to the Scottish hydrogen industry as part of the Scottish Government’s £180m Emerging Energy Technologies Fund (EETF). The funding aims to accelerate as many projects as possible from the pilot stage through to commercialisation. In addition, £10m in funding will prioritise research and innovation via the creation of the Scottish Hydrogen Innovation Fund.

Actions targeting the transport sector specifically include:

- Developing funding support for zero-emission vehicles that is complimentary to subsidy available for hydrogen production.
- Facilitating further innovation in hydrogen technology, particularly for heavy-duty vehicles, to make Scotland a global centre for expertise for innovation in hydrogen mobility.
- Working with the Energy Skills Partnership on the Transport Hydrogen Skills Development to support a growing Scottish skills base in hydrogen for transport

7.2.3 Carbon neutral Islands

The Carbon Neutral Islands project aims to provide support to Scottish islands in becoming carbon neutral by 2040. This involves collaboration between the Scottish Government, local authorities and island representatives [67].

The National Islands Plan provides a framework for action to improve outcomes for island communities, setting out 13 strategic objectives and over 100 commitments. Strategic Objective 3 is focused on the improvement of transport services, and within this, commitments have been made to produce a long-term plan and investment programme to improve ferry services while reducing emissions. Further commitments have been made to develop a new Ferries Plan which ties in with wider objectives of the Scottish government including the National Transport Strategy. While these commitments have been delayed by the COVID-19 pandemic, a draft Ferry Plan for consultation is expected in December 2022.

7.2.4 Aviation Strategy – consultation

Scotland's first ever Aviation Strategy is expected to be published in early 2023. To inform the Strategy, a consultation was launched in October 2021 gather views on how the Scottish Government should collaborate with others to achieve its vision for aviation. A key theme emerged that both public and private sector investment will be necessary to enable the commercialisation of SAFs. In addition, there is appetite for domestic SAF production and for a long-term policy framework with incentives to generate confidence in zero emission aviation and attract private investment in SAFs.

7.3 International policy

Various policy measures and initiatives exist outside Scotland and the UK which are aimed at increasing the production and use of LCFs.

The EU parliament recently approved the ReFuel EU aviation initiative in July 2022 [68]. Under the initiative, aviation fuel must include 2% SAF from 2025, 37% in 2035, rising to 85% by 2050 – a significant increase from the Commission's original proposal of 63% SAF by 2050.

Measures to support SAF production deployment which have been considered within the impact assessment of the ReFuel EU initiative include contracts for difference. This measure, while yet to be implemented for LCFs, could help reduce uncertainty for SAF producers by ensuring a certain price level for SAFs. By bridging the gap in price between SAFs and conventional fuels, demand from aviation service providers would be expected to increase. In turn, price certainty for a given timeframe could also facilitate private investment.

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a global market-based measure to reduce emissions from the aviation sector. CORSIA aims to compliment other measures by offsetting the CO_2 emissions which cannot be abated through technological or operational improvements [69].

In comparison to international policy of LCF within aviation the UK, through the Jet Zero Strategy, is largely aligned with targets for production set out in the ReFuel EU initiative, at least in the lead-up to 2030. The forthcoming Scottish Aviation Strategy could provide an opportunity to build on UK wide policy through additional measures and incentives.

8 Conclusions

Reflecting on Scotland’s Climate Change Plan proposals, this evidence review finds that there is a role for LCFs to play in meeting plan objectives, particularly in aviation and maritime sectors, and potentially for some limited applications in road transport. Relevant objectives include:

- Continue work to establish a zero emissions heavy duty vehicle programme.
- Decarbonise scheduled flights within Scotland by 2040.
- Create the world’s first zero-emission aviation region in partnership with Highlands and Islands Airports.
- Decarbonise Scotland’s passenger rail services by 2035.
- Ensure 30% of ferries in Scottish government ownership are low emission by 2032.

Policy support from Scottish Government and, in some cases, intervention could allow the most promising feedstocks and conversion pathways to bear fruit, in time to meet policy objectives. The overall role for LCFs in Scotland achieving its emissions reduction goals is clear. They will be essential in decarbonising the aviation and maritime sectors. There are little to no LFCs deployed in the aviation or maritime sectors at present, although our research indicates that this is likely to change dramatically over the coming years. However, there is no “silver bullet” solution in terms of a preferred feedstock or fuel production route across all relevant sectors.

8.1.1 Road transport

- LCFs currently play a role in decarbonising the road transport fleet, where bioethanol and FAME biodiesel are blended with fossil petrol and diesel respectively. However, this will only be an interim step before full electrification and only for the heaviest long distance vehicles.

8.1.2 Aviation

- The technical options for deploying LCFs in the aviation sector are relatively clear. This is because fuels must be certified before they can be used. The leading candidates are HEFA, FT-SPK and ATJ.
- Demand for SAF in the short term is likely to be met by HEFA as this is the most developed and cheapest production route. However, it is produced using UCO, which is a finite resource and also an important feedstock for decarbonising road transport. Consequently, HEFA is subject to a cap in the SAF mandate and cannot be a long-term, scalable solution.
- FT-SPK and ATJ can both utilise lignocellulosic feedstocks, which are abundant in Scotland. However, our analysis suggests that the FT-SPK route offers greater GHG savings compared to ATJ for a given feedstock. The viability of these production routes is dependent on the availability of lignocellulosic feedstocks. The quantity of this class of feedstocks that could be available in Scotland is a major source of uncertainty. Furthermore, the competition for lignocellulosic feedstocks from the heat and power sectors is likely to be significant, particularly if Scotland is to realise its BECCS ambitions.
- FT-SPK can also be produced from renewable electricity and CO_2. This route offers the biggest GHG emissions savings. Furthermore, sufficient investment in the required infrastructure would mean that feedstock supply is not likely to be an issue.

8.1.3 Maritime

- Green ammonia appears to be the preferred option towards the decarbonisation of the maritime sector. The advantage of using green ammonia is that it has a higher energy density by volume than hydrogen and does not produce CO_2 when combusted. However, significant developments in infrastructure and, to a lesser extent, engine technology are needed before it can be deployed.

- Green methanol was identified as an alternative as it offers similar GHG saving, and the infrastructure for handling green methanol is more developed than for ammonia.
- For green ammonia and green methanol domestic supplies to increase, expansion of green hydrogen infrastructure will be required.

Deployment of LCFs in Scotland will continue to be facilitated by the RTFO and from 2025 by the SAF mandate. Scotland’s continued commitment to invest in hydrogen infrastructure will be of great benefit to the deployment of LCFs.

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Appendix A Abbreviations

Abbreviations	
ATJ	Alcohol-to-Jet Synthetic Paraffinic Kerosene, ATJ used throughout report as an abbreviation of ATJ-SPK
BECCS	Bioenergy with Carbon Capture and Storage
BEV	Battery Electric Vehicle
CCC	Climate Change Committee
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
DAC	Direct Air Capture
e	Equivalent
EV	Electric Vehicle
FAME	Fatty Acid Methyl Ester
FCEV	Fuel Cell Electric Vehicle
FT-SPK	Fischer Tropsch - Synthetic Paraffinic Kerosene
G	Grams
GHG	Green House Gas
gCO_2e/MJ	Grams of CO_2 equivalent released per Megajoule of fuel produced
HEFA	Hydro processed Esters and Fatty Acids
HGV	Heavy Goods Vehicle
HVO	Hydrotreated Vegetable Oil
LCA	Life Cycle Assessment
LCF	Low Carbon Fuel
LULUCF	Land Use, Land-Use Change and Forestry
MJ	Megajoule
NRMM	Non-Road Mobile Machinery
RCF	Recycled Carbon Fuels

RFNBO	Renewable Fuels of Non Biological Origin
RTFO	Renewable Transport Fuel Obligation
SAF	Sustainable Aviation Fuel
SRC	Short Rotation Coppice
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TRL	Technology Readiness Level
UCO	Used Cooking Oil
UCOME	Used Cooking Oil blended with Methyl Ester
xEV	Electric Vehicle (fuel cell or battery)
ZE	Zero emission

Appendix B Fuel products, feedstocks and pathways

Fuel / products	Possible feedstocks	Processes / pathways - description
Hydrotreated Vegetable Oil (HVO)	Vegetable oils, and Waste oils (Used cooking Oil - UCO)	Through a complex process, vegetable oils are converted into drop-in type diesel which can be used up to high fractions in road transport
Hydro processed Esters and Fatty Acids (HEFA)	Plant and animal lipids	Via a complex process, vegetable oils are converted to sustainable aviation fuel that can be used in 50% blends with fossil jet fuel
Bio-gasoline	Sugar and starch crops, fibre and grass cellulosic crops, oil crops, crop residues, manures and organic waste, wood products	Direct combustion for heat/ power, conversion using transesterification (the process in which nonedible oil is allowed to chemically react with alcohol), fermentation, anaerobic digestion (through which bacteria break down organic matter).
Used Cooking Oil blended with Methyl Ester (UCOME)	Used cooking Oil (UCO)	Made from used cooking oil and transesterification, the finished methyl ester, UCOME, is a second-generation biofuel increasingly favoured by blenders to satisfy the mandated (EU RED II) shift to waste-based biofuel.
Fatty Acid Methyl Ester (FAME)	Tallow (animal fat) - category 1, Used cooking Oil (UCO); Brown grease; crude glycerine; food waste; Sewage systems FOG	Through transesterification which converts fat oils to biodiesel and a by-product of glycerine.
Fatty Acid Methyl Ester (FAME)	Oil crops	Transesterification of fats (usually from vegetable oil) with methanol.
Biodiesel	Tallow (animal fat), Used cooking Oil (UCO); Brown grease, Sugar beet betaine residue;	Hydrothermal liquefaction (HTL) where organic matter is mixed with water and exposed to high temperature and pressure to be converted to oil.
Bioethanol	wheat, sugar beet	Fermentation (chemical changes through the action of enzymes) of 1st generation feedstock.
Bioethanol	Tallow, Used cooking Oil (UCO); Brown grease	Feedstock can be broken down by steam explosion and fermented to produce bioethanol.
Methanol	Lignocellulosic feedstocks	Anaerobic digestion (through which bacteria break down organic matter).

Ammonia - for shipping	Natural gas	Steam methane reforming (SMR) to produce hydrogen followed by the Haber process to produce methane. Difficult to store (toxicity) and energy intensive.
Hydrogen (blue)	Natural gas	Blue hydrogen is produced from natural gas through the process of steam methane reformation (SMR). Besides the key product (H2) carbon dioxide is also released. Concept conventionally coupled with CCS (Carbon Capture and Storage).
Hydrogen (green)	Water	Green Hydrogen is produced through electrolysis of water (splitting of water). Electrolysers can be quite energy-intensive however, the use of clean renewable electricity (solar or wind) emits no carbon.
E-fuels	hydrogen, renewable energy	Renewable Fuels of Non-Biological Origin (RFNBO). Conversion to renewable electricity applied to hydrogen production via water electrolysis. Hydrogen then combined with CO2 captured via CCS (fossil-derived or biogenic).
RFNBO biomethanol for shipping	Glycerine from biodiesel production; Black liquor from pulp and paper industry; Biogas/ natural gas	Gasification of these feedstock into syngas and its optimisation through the addition of CO2 (fossil-derived or biogenic) and H2 (green); Or methane reforming of biogas/ natural gas
Methanol	CO_2 and Hydrogen	Catalytic conversion (using catalysts to convert heavy hydrocarbons, chemicals or fuels to light hydrocarbons, chemicals or fuels) to methane from hydrogen.
e-methanol	Green hydrogen and biogenic CO_2	RFNBO - Conversion of renewable electricity applied to hydrogen production via water electrolysis. Hydrogen then combined with CO2 captured via CCS (fossil-derived or biogenic)
Ethanol	Steel mill waste, fossil, CAS gas	Anaerobic digestion (through which bacteria break down organic matter).
Fischer Tropsch synthesized Paraffinic kerosene (FT-SPK)	Energy crops and lignocellulosic biomass and other solid waste	Biomass gasification and Fischer Tropsch process
Co-processing of up to 5 vol% fats and oils - kerosene	Used cooking Oil (UCO); oil-based crops	Vegetable oils can be co-processed in existing mineral oil refineries up to a fraction of about 5-10% simultaneous with the otherwise fossil feedstock
Alcohol to Jet fuel (long term)	Ethanol (from sugar, CO gas and syngas), Iso-butanol (sugar)	Conversion of sugar through fermentation, CO gas fermentation, Sugar to butanol fermentation; catalytic thermochemical conversion of syngas to ethanol

Appendix C LCF descriptors

LCFs can be classified as biofuels, RCFs or RFNBOs depending on the feedstock that is used in their production (Figure 1). However, it is also helpful to recognise that LCFs can generally be assigned to one of the following categories relating to their use.

Blending Components

LCFs that can be blended with fossil fuels up to a limit ("blend-wall") are known as blending components or non-fungible LCFs. Bioethanol and FAME are the most common examples of blending components. Blending components are relatively easy to make and consequently, relatively cheap.

Blending components cannot be mixed in significant quantities with fossil fuels. This is because they have chemical and physical properties that are notably different to fossil fuels. Most commonly, the difference in properties is a result of blending components containing oxygen atoms (e.g., bioethanol, FAME), whereas fossil fuels do not. Consequently, adding significant quantities of these components to fossil fuels negatively impacts their in-engine performance, and sometimes the fuel handling infrastructure.

Blending limits are imposed on these components via fuel specifications. For example, the fuel standard EN 590 limits the blending of FAME biodiesel with fossil diesel to 7% and the fuel specification EN228 limits the blending of bioethanol in gasoline to 10%. Therefore, the impact that blending components can have on reducing GHG emissions of the overall transport fleet is inherently limited.

Drop-in Fuels

LCFs that can be blended with fossil fuels with no-upper limit are known as drop in fuels or fungible LCFs.

Drop-in fuels can either completely replace their fossil equivalents or be blended in large quantities. The reason that drop-in fuels have no blending limit is that they are chemically very similar to fossil fuels. They are comprised of carbon and hydrogen atoms only i.e., do not contain any oxygen, unlike blending components. Therefore, drop-in fuels generally have minimal adverse effects on fuel performance. Consequently, drop-in LCFs have the potential for a much more significant reduction in GHG emissions compared to blending components.

However, drop in fuels are usually produced by more complex processes than blending components or speciality fuels, and are consequently more expensive than blending components.

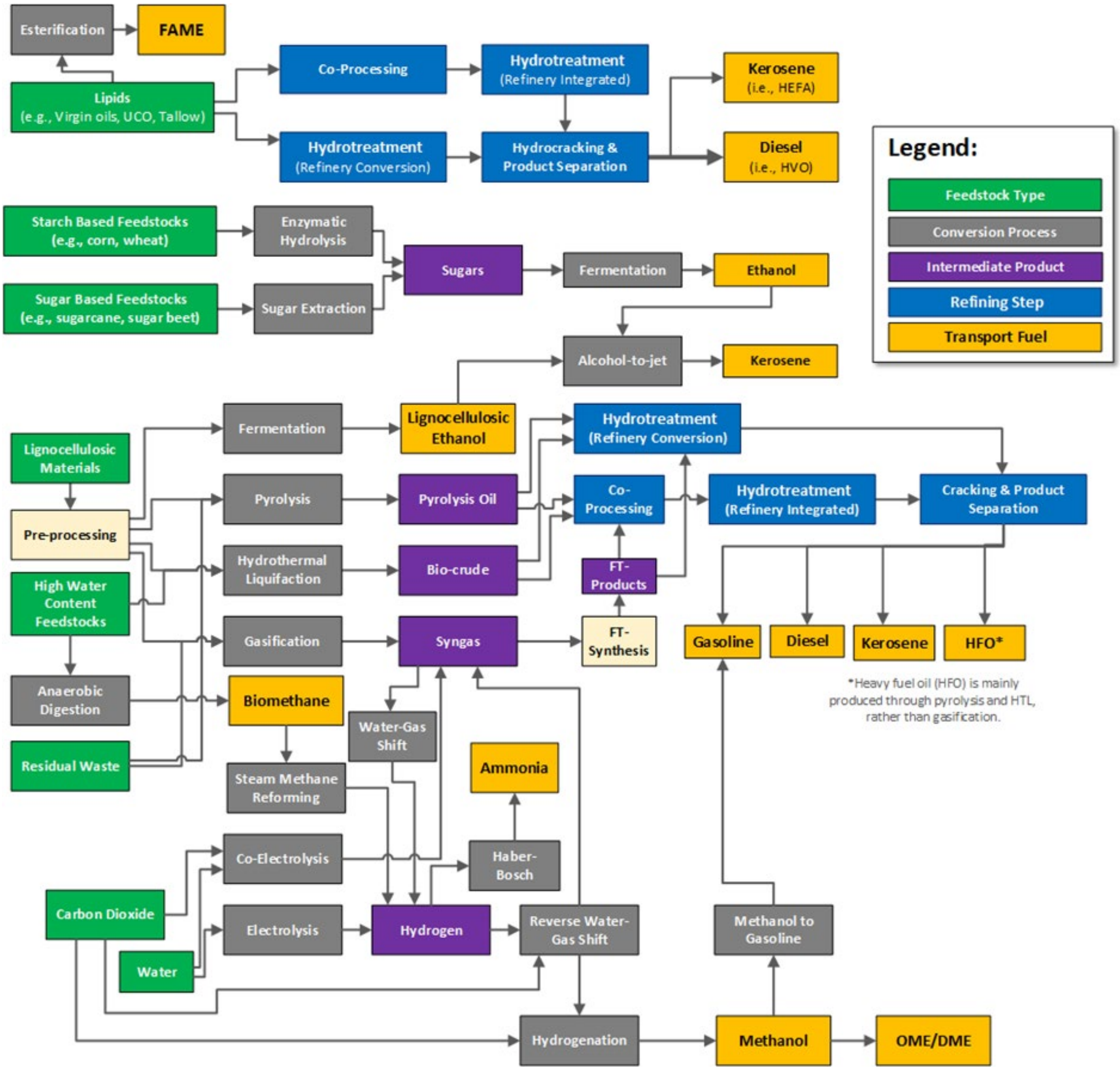
Drop-in fuels are not currently deployed commercially at a large scale. The most promising examples are hydrotreated vegetable oil (HVO) and hydroprocessed esters and fatty acids (HEFA).

Speciality Fuels

LCFs that are not blended with fossil fuels and require specialised powertrains are known as speciality fuels. Speciality fuels generally necessitate some modification/replacement to existing infrastructure before they can be deployed. Examples of speciality fuels include hydrogen, ammonia and methanol.

This is a major disadvantage to this class of LCFs. For example, the deployment of hydrogen, ammonia or high concentration alcohol fuels in the existing fleet is not possible without significant modification or replacement. Therefore, the impact of speciality fuels is limited by the availability of the technology that can utilise them.

Appendix D Schematic overview of LCF production routes



*Heavy fuel oil (HFO) is mainly produced through pyrolysis and HTL, rather than gasification.

Appendix E LCF review

The following table provides an illustrative range of examples of fuel types and pathways that have been considered in the compilation of this report and in the literature review. This list is not intended to provide a comprehensive list of low carbon fuels but highlights the difference in technology readiness level between similar LCFs for the different transport modes depending on the feedstock/ production routes.

Sector	Fuel type	Feedstock	Processing pathway	TRL
All	Biohydrogen	Forest residue	Gasification and hydrogenation of syngas	No data
All	Biomethane	Draff - whiskey by-product	Pretreatment of draff and anaerobic digestion	No data
Road	Bioethanol	Agricultural residue	Saccharification - Fermentation	6-8
Road	Bioethanol	Sugar and starchy feedstock	Fermentation	8-9
Road	Bioethanol	Draff - Whiskey by-product	Dark fermentation	No data
Road	FAME Biodiesel	Vegetable/ Tallow	Transesterification of vegetable/ animal fat	8-9
Road	FAME Biodiesel	Used cooking oil	Transesterification of vegetable/ animal fat	8-9
Road	e-gasoline	CCS-CO2 and green hydrogen	E-fuel route	3-5
Road	HVO Biodiesel	Used cooking oil	Hydrogenation of used cooking oil using green hydrogen	8-9
General	Green hydrogen	Water	Water electrolysis using renewable energy	6-7
General	Pink hydrogen	Nuclear-derived renewable energy and water	Water electrolysis using renewable energy	3-4
General	Waste-to-hydrogen	Municipal solid waste	Gasification to hydrogen	No data
Maritime	Green ammonia	Conv. Captured N2 and green hydrogen	Haber Bosch process	No data
Maritime	Bio-based Dimethyl Ether (DME)	Dry biomass	Thermal gasification and dehydration of resulting methanol	No data
Maritime	Biomethanol	Forest and agricultural residue	Gasification and methanol synthesis	7-9
Maritime	Biomethanol	Municipal solid waste, black liquor from paper and pulp industry	Gasification and methanol synthesis	7-9
Maritime	e-Methanol	CO2 from Flue exhaust or capture	E-fuel route	6-8
Maritime	e-DME	CO2 from Flue exhaust or capture	E-fuel route	6-8

Maritime	Bio-ammonia	Hydrogen from SMR and biomass gasification and atmospheric nitrogen	Haber-Bosch process	8-9
Maritime	Blue ammonia	Co-produced nitrogen and SMR-drawn hydrogen	Haber-Bosch process with carbon capture and storage	No data
Aviation	Alcohol-to-Jet (ATJ)	Agricultural or forestry residue	Enzymatic breakdown, fermentation and hydrogenation	6-8
Aviation	e-kerosene	CO2 from Flue exhaust and green hydrogen	E-fuel route	6-8
Aviation	Fischer Tropsch - Synthetic Paraffinic Kerosene (FT-SPK)	Agricultural or forestry residue	Biomass gasification and FT synthesis	7-8
Aviation	Fischer Tropsch - Synthetic Paraffinic Kerosene (FT-SPK)	Municipal Solid Waste	Gasification of MSW and FT synthesis	7-8
Aviation	Hydroprocessed Fatty Acid Esters and Fatty Acids-synthetic paraffinic kerosene (HEFA-SPK)	Lipids	Hydroprocessing of lipids	8-9

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