Cerulogy

Scrutinising the future role of alternative fuels in delivering aviation decarbonisation

Part 2 – waste management and use

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Disclaimer

Contents

Glossary

Alternative aviation fuel – aviation fuels not produced from crude oil, including aviation biofuels (biojet) and aviation e-fuels (e-jet).

Biofuels (including biojet) – fuels produced from biomass.

Carbon footprint – see GHG intensity.

Carbon intensity – see GHG intensity.

CCS – carbon capture and permanent storage.

CORSIA – ICAO's Carbon Offsetting and Reduction Scheme for International Aviation.

DfT – UK Department for Transport.

Direct emissions – when we talk about direct emissions in the context of alternative fuels we are talking about the emissions that are within the control of operators somewhere in the supply chain for a given alternative fuel pathway. Note that this differs from the way that direct emissions are defined in company accounting under the GHG protocol, where direct include only emissions within the control of the company being assessed, and emissions under the control of third parties in the supply chain are characterised as indirect.

Downstream – processes that occur later in the supply chain (i.e. closer to the point at which a product is delivered to an end user).

E-fuels (including e-jet) – fuels produced from electricity be generating electrolytic hydrogen and synthesising it into hydrocarbons (or other fuel molecules).

Embedded emissions – the GHG emissions associated with the production of a material or energy stream used as an input for another process.

GHG – greenhouse gas.

GHG intensity – the GHG intensity of a fuel or of a process is a characterisation of the amount of carbon dioxide and other greenhouse gases that are released due to the production and use of the fuel or the application of the process. For fuels, in this report we express GHG intensity in terms of grams of carbon dioxide equivalent emissions (on a GWP100 basis) per megajoule of chemical energy in the fuel on a lower heating value basis. This unit is abbreviated to gCO_2e/MJ.

Indirect emissions – when we talk about indirect emissions in the context of alternative fuels we are talking about emissions that are generally outside the control of operators within the supply chain. This includes emissions from land use changes that are market driven and do not generally occur at the farms on which feedstock batches are actually produced and emissions (or GHG reductions) associated with displacement of materials out of existing markets. Note that this differs from the way that indirect emissions are defined in company accounting under the GHG protocol, where these sorts of market-mediated indirect emissions are normally treated as outside even Scope 3.

IPCC – Intergovernmental Panel on Climate Change.

LCA – lifecycle analysis, the practice of assessing the full set of emissions associated with production, use and disposal of a product or service.

LCA score – for LCA of climate impacts, the LCA score is an indicator of the GHG intensity, determined not only by the characteristics of the fuel or process but by the rules of the LCA framework.

Physical CO_2 emissions – in this series of reports, when we talk about 'physical CO_2 emissions' we mean the CO_2 emitted from a specified process ignoring lifecycle considerations and conventions such as zero accounting of biogenic CO_2.

REFuelEU – the EU's regulation setting targets and rules for alternative aviation fuel use out to 2050.

Renewable Energy Directive (RED) – the EU's framework for supporting renewable energy, including renewable fuels in transport.

Renewable Transport Fuel Obligation (RTFO) – the UK's framework for supporting renewable fuels in transport.

Sustainable aviation (SAF) – see alternative aviation fuel (AAF).

Synthetic aviation fuels – hydrocarbon fuels certified for aviation use produced from non-oil resources (e.g. biomass, electrolytic hydrogen, natural gas, coal).

True emissions – when we say 'true emissions' in this report we mean the change in total global emissions (associated with a given action) that we could identify if we were omniscient and had perfect foresight – in practice, the true emissions are not known.

Upstream – processes that occur earlier in the supply chain (i.e. closer to the point of raw material extraction).

Summary

Most people intuitively understand that it is good to find a productive use for something that was previously disposed of as a waste. In the UK and around the world there is a drive to reduce waste generation, to increase recycling rates, and to reduce the amount of residual waste that is sent to landfill. In this context, the potential to produce alternative aviation fuels from waste material instead of from crude oil has obvious appeal.

While the basic premise seems hard to argue with, there are questions to resolve about whether any specific biofuel feedstock is truly a waste material or has other productive uses, and about what the net GHG benefit is from moving resources from a given existing use or disposition into fuel production.

Currently, the UK RTFO requires that all new biofuel feedstocks must be assessed before they may be reported as wastes or residues, including considering any alternative uses, and this is currently one of the more stringent assessment processes under any biofuel regulation in the world. Once a biomass feedstock is identified as a waste or residue in the RTFO then it is permitted to calculate its lifecycle emissions assuming zero emissions up to the point of collection, and it becomes eligible for additional support through double counting under the main RTFO, and unless it is a 'segregated oil or fat' it is eligible to be used as feedstock for development fuels.

The UK Government has also expressed the intention to bring a new category of 'recycled carbon fuels' (RCFs) into the RTFO, allowing fuels produced using fossil energy from industrial flue gases or from 'refuse derived fuel' (RDF) from municipal waste to be counted.

Waste and residual resources can be characterised as having a 'rigid' supply – the amount of a waste or residue that is produced is independent of how much demand there is for fuel feedstock. It is instead determined by the amount of other co-products that are produced or by the amount of material that people throw away. Assessing the net GHG benefits of using these materials as biofuel feedstocks therefore requires the use of some of the consequential LCA ideas discussed in part 1 of this series of reports, and the identification of a counterfactual fate for the material. If the waste/residue had some alternative use, such as an alternative energy recovery route, then diverting that resource to biofuel production means that a replacement material or service is needed to support that existing use. If the waste/residue had no alternative use, then there may still be emissions implications from diverting it from an alternative disposition. For example, diverting biodegradable material from landfilling can reduce methane emissions. The appropriate counterfactual for a given material can sometimes change over time – for example the UK Government has indicated the goal of eliminating biodegradable material in landfill, and therefore at some point landfilling should not be part of a counterfactual fate for that material. A form of this consequential LCA is already present in rules for assessing the GHG emissions for RCFs under the RED, and is proposed to be included in rules for the RTFO.

The proposed RTFO rules[1] would take electricity generation at 26% thermal efficiency as the counterfactual for RCFs in all cases. While at present some of the fossil material in RDF might otherwise have been landfilled, the UK Government has argued that because it is intended that the amount of material landfilled will be reduced over time this is not an appropriate

[1] Which we would assume will also be applied under a UK SAF mandate.

counterfactual in the longer term. A counter argument to this reasoning would be that if RCF production is part of the portfolio of measures to reduce landfilling then that would suggest that landfilling might be exactly the most appropriate counterfactual. This makes an important difference to how we understand the GHG impact of increased RCF production. If landfill is the counterfactual, then the fossil carbon would otherwise have been stored semi-permanently. In that case, while RCF production delivers benefits from a waste management perspective, from a climate perspective the outcome it is similar to burning conventional fossil fuels. If instead the counterfactual is incineration with low-efficiency energy recovery, then switching to a more energy efficient RCF production process could deliver significant benefits. In the short term, we conclude that the UK Government may be conflating a waste-management benefit with a climate benefit, in which case the regulatory LCA will exaggerate the climate benefits of RCF use. We would encourage the Department for Transport to continue to carefully consider the role of RCF production in broader waste policy before finalising the LCA requirements for a new category of RCFs under the RTFO. In the longer term, if landfilling truly approaches elimination in the UK then the Government counterfactual may become more clearly justified.

Changes in the disposition of wastes and residues can also have implications for inventory accounting. Methane emissions from landfill are included in the national inventory for waste emissions under IPCC guidelines, whereas combustion emissions from fossil waste incineration are included in the energy sector inventory if energy is recovered or under the waste inventory if energy is not recovered. Changes in the amount of carbon stored in harvested wood products that reach end of life should be considered in the land use, land use change and forestry inventory. National inventory reporting of these emissions relies on estimates and assumptions, for example on the fraction of fossil carbon in each waste stream. Because of these estimates, national inventories will not exactly reflect real changes in emissions when disposition of waste material changes.

In company GHG reporting, the rules currently only require emissions from the disposal of wastes[2] to be counted by companies as Scope 3 emissions if those wastes are disposed of without energy recovery or other further use (i.e. by landfilling or by incineration). If energy is recovered, then the waste-generating company is permitted to count zero emissions in Scope 3 and the company utilising the produced energy should account for the released CO_2 as a Scope 2 emission. This treatment raises an issue if we are producing RCF fuels from waste and treating them as low emission fuels by comparing them to a counterfactual – the actual physical emissions from combusting the waste material could go missing from the company GHG inventories altogether. One resolution to this inventory inconsistency would be to reinstate the emissions associated with CO_2 release from wastes into the Scope 3 emissions of waste generating companies, and this would have the advantage of holding companies more responsible for generating waste in the GHG accounting.

[2] If the waste requires treatment to be made safe for disposal any associated emissions should be counted in the inventory of the waste-generating company.

1 Introduction

The global market for alternative fuels is currently dominated by biofuels, and most biofuel production uses agricultural commodities (grain, vegetable oil, sugar crops) as feedstock. This has led to concerns being raised about the impacts of biofuel demand on food markets and as a driver of deforestation through indirect land use change. The use of non-primary materials (often characterised as 'wastes and residues') is therefore seen as a way to mitigate some of the potential negative implications of crop-based biofuel production, as it has generally been assumed that utilising materials that have a low intrinsic market value avoids interfering in agricultural markets. Some jurisdictions have therefore offered higher levels of support to biofuels produced from waste and/or residual materials than biofuels from food crops, for example through the 'double counting' mechanism in the EU Renewable Energy Directive (RED)[3], which is also applied in the UK's Renewable Transport Fuel Obligation (RTFO). Biofuel producers have also been keen to find ways to utilise waste or residual materials in order to reduce feedstock costs – in the most favourable case, materials like municipal solid waste (MSW) might even be available at negative cost to the biofuel producer, as waste-holders can save money on disposal. There is a tension between achieving lower priced feedstock and the offer of enhanced regulatory value, because regulatory bonuses for using certain feedstocks increase their value to fuel producers. This has led to counter-intuitive situations such as used cooking oil (UCO) trading for a higher price than virgin vegetable oil (van Grinsven et al., 2020). Higher prices on waste or residual materials may be necessary to cover the costs of collection and aggregation, but they create an incentive for a simple type of mislabelling fraud – incorrectly stating that biofuels are produced from feedstocks with waste status when they are not could be a simple way to increase revenue.

The underlying premise behind preferential treatment for the use of wastes and residues in the biofuel supply chain is that these are materials that either entirely lack alternative uses or that only have very low value alternative uses (value could be understood in solely financial terms, or more broadly as value to society). By that premise, utilising these resources for biofuel production is understood as an obvious win-win in terms of economic value and climate change mitigation. If, however, the world is actively seeking to minimise the generation of waste and to find productive uses for all available resources, this win-win outcome may become less obvious. Certainly there are cases in which materials that are widely referred to as either wastes or residues actually have perfectly sensible existing uses, and these existing uses could be affected (or eliminated) if alternative fuel policy creates strong incentives to favour use as biofuel feedstock. Considering these counter-factual questions is vital if assessing the net carbon implications of increased alternative fuel use from any given resource on a consequential basis.

1.1 'Recycled carbon fuels'

Interest in the use of wastes and residues as alternative fuel feedstock is not limited to biofuels. The RED has also introduced a category of 'recycled carbon fuels' (RCFs), alternative fuels that are produced taking advantage of chemical energy of fossil origin in waste streams.

[3] The double counting provision allows Member States to count the energy in biofuels from certain identified wastes and residues twice towards compliance with national renewable energy targets, and in many Member States this is passed through to biofuel suppliers as a double incentive.

Examples of such waste streams could include carbon monoxide rich flue gas from steel manufacture, waste plastic and tyres, and used mineral lubricating oils.

In the UK, the Government has consulted on adding two types of RCFs as eligible fuels under the RTFO. These are distinguished by feedstock, the first being fuels from the fossil component of refuse derived fuel (RDF)[4], and the second being fuel derived from industrial waste process gas (UK Department for Transport, 2021b). The UK Government argued that making RCFs from RDF eligible for the RTFO could enable the production and supply of additional volumes of renewable fuel as RDF includes a biogenic fraction that cannot be readily disaggregated but could be co-processed with the fossil fraction.

Under many existing LCA and inventory approaches, the GHG emissions from combusting fuels containing fossil carbon would be assigned to the fuel, and therefore an RCF could not be treated as delivering GHG benefits under these frameworks[5]. Identifying a GHG benefit requires adding an element of consequential thinking – i.e. identifying that the alternative possible use or disposition of the fossil resource leads to higher net emissions than the use of the resource to produce transport fuels, and crediting the RCF for the difference. LCA approaches for RCFs are further discussed in section 4.

1.2 Co-products, by-products, residues and wastes

When discussing the potential role of wastes as feedstock for transport fuels, it is important that we understand precisely which materials should be characterised as wastes. All wastes are materials generated as an incidental result of delivering some other material or service, but not all materials produced as an incidental result of producing a material or service are wastes. Some processes deliver a range of products of various values and uses. There are various terms that are used to refer to the different outputs of any particular process:

- 'Products'. The term products generally refers to the outputs of a process that have some significant value (although there is no generally accepted definition available for what constitutes 'significant') and that constitute the main aims of a process. Producing more of a product while leaving all other outputs equal is considered beneficial as it increases potential revenue. Within products sub-terms are used including:
    - 'Main product(s)'/'principal product(s)'. One or more products that can be characterised as the main aims of a process.
    - 'Co-products'. Two or more products of a process both of which deliver significant value. This will always include any main or principal products, but may imply a broader set of outputs. Sometimes co-products are identified as the set of outputs the prices of which determine the overall use of a process – i.e. if the price for one co-product increases we would expect the supply of that

[4] From which recyclable plastics should have been removed.

[5] This is not true for aviation biofuels, because there is a convention in LCA that CO_2 emitted from biomass combustion should be treated as a zero emission on the assumption that it was recently absorbed from the atmosphere and combustion closes this cycle. See also Part 1 of this series of reports.

co-product to be increased in response to the price signal[6]. In the lifecycle analysis for the RED only outputs identified as co-products have process emissions allocated to them (see section 4.1).

  - ‘By-products’. Products from a process that are not main aims of the process. This will not include products identified as main or principal, but the use of the term by-products in some descriptive systems may overlap with the use of the term co-products in others. By-products will always have a lower total value associated with them than the main products, and will generally also have a lower price per unit mass. The use of the term by-products may overlap with the use of the terms residues and wastes.

- ‘Residues’. Outputs that are not an aim of the process. The process operators are generally indifferent to the quantity of residues produced, i.e. it would not be considered disadvantageous if residue yields were reduced. In the terminology used by the RED, residues are outputs that are not a main aim of a process but that the holder does not intend to discard. In some contexts, however, the term residues may be used for materials that will be discarded – for example, it is common to refer to plant material left behind in the field after crop harvesting as residues, irrespective of whether they can or will be collected for use.

- ‘Wastes’. The lowest value and least desirable of the output products from a process. In the context of the EU ‘Waste Framework Directive’ (WFD)[7] a waste is defined as a material that the holder discards, intends to discard or is required to discard. This also provides the basis of the functional definition of a waste in EU and UK biofuel legislation. A process operator would generally prefer to minimise the production of waste as it may be associated with a cost of disposal. Some operators nevertheless habitually refer to all low value outputs of a process as wastes even if they have potential uses.

Different legislative systems use different terminologies, and the precise legal implications of the terminologies used are not always obvious. The WFD uses the terms ‘waste’ and ‘by-product’ for substances that are not the ‘primary aim’ of a production process. The RED identifies ‘co-products’ as substances that are the primary aim of a production process, but refers to residues and wastes rather than by-products and wastes. The definition of a residue under the RED is, “a substance that is not the end product(s) that a production process directly seeks to produce; it is not a primary aim of the production process and the process has not been deliberately modified to produce it.” This of course begs the question of how one identifies the set of co-products that ***are*** the primary aim of a production process, and of what constitutes a modification to a process. It is broadly accepted that identifying the primary aim of a process requires reference to the relative value of the outputs, but there is still no established rule available that can be applied in all situations (cf. ICF International, 2015; Ro et al., 2023).

To illustrate the production of co-products, residues and wastes consider the example of the process of biodiesel production from used cooking oil (UCO). The main product of this process

[6] Depending on the flexibility in the ratio of outputs this may imply either an increase or reduction in other co-product supply. If the output ratio is inflexible (e.g. vegetable oil and meal from oilseed crushing) then to increase the supply of Co-product A you must also increase supply of Co-product B. If the ratio of outputs is flexible (e.g. in oil refining) then you could increase the supply of Co-product A at the expense of reducing the supply of Co-product B.

[7] The UK waste framework remains consistent with that of the EU directive.

is biodiesel – most of the mass of the feedstock ends up in the biodiesel product, and it also accounts for the bulk of the value. A smaller amount of glycerine is also produced as a result of the transesterification process. Glycerine is a product with a range of potential applications. Malins (2017a) notes that some glycerine is refined allowing applications in chemicals, pharmaceuticals, some is used without refining as an additive in animal feed, and some may be used in energy recovery applications including as an anaerobic digester feed. As glycerine has an existing market and value it is understood not to be a waste, but as it has much lower value (both in terms of price per tonne of crude glycerine produced and total value per tonne of UCO processed) than the produced biodiesel it is generally understood to be a by-product or residue rather than a co-product. Finally, in the process of filtering and preparing the UCO for transesterification some amount of water and organic material will be extracted (bits of chips, batter etc. left in the frying oil). This is material with no market and would generally be considered a waste.

In alternative fuel policy, whether or not a material is characterised as a waste can be important because it can determine the regulatory treatment for which fuels produced from that material are eligible. This can include eligibility for extra incentives, and eligibility for simplified sustainability reporting systems. The availability of fuel production pathways can complicate the identification of wastes, however, as it may not always be obvious whether a material that is used as a fuel feedstock would otherwise have been discarded. The underlying assumption of the WFD is that operators will seek to minimise the amount of material to be classified as waste because waste classification under WFD is associated with handling and disposal costs. Incentives in energy policy for the utilisation of wastes can invalidate that underlying assumption, because value may now be maximised by increasing the amount of material receiving waste classification. Indeed, an ambiguity is introduced into the characterisation of outputs for the purpose of energy policy, because by definition when a material becomes an energy feedstock it starts to have a use. This can make it harder to identify whether a given material that is used in an energy application can be considered a waste or not; or, to put it differently, in which circumstances could an existing energy use be considered a form of 'discarding'?

1.3 Waste to fuel technologies

1.3.1 Transesterification and hydrotreating

The most well-developed production pathways for waste-based biofuels are the conversion of vegetable oils and rendered animal fats into biodiesel by transesterification (reacting with methanol) and into renewable diesel/renewable jet fuel by hydrotreating (reacting with hydrogen). Transesterification is a relatively simple chemical process that can be undertaken at a relatively small scale, and therefore the development of the EU biodiesel industry included the opening of large numbers of smaller enterprises collecting and processing used cooking oil from their local catchments – although the market has been rationalised over time with smaller operators closing and the average size of EU biodiesel processors increasing. Hydrotreating is a newer more capital-intensive technology that requires economies of scale and a ready supply of hydrogen, and therefore hydrotreating facilities tend to be as big or bigger than the biggest biodiesel processors. Hydrotreating differs from transesterification by making it possible to produce a jet fuel substitute, whereas biodiesel is not appropriate for aviation use.

The supply of waste vegetable oils is already well exploited by the biodiesel industry, and therefore expansion in renewable jet fuel production from these resources is likely to come at the expense of either on-road biodiesel production or of other users of the resources (see section 4.2).

1.3.2 Fermentation to ethanol

Waste or residual substances that contain starches or sugars can be fermented to ethanol using first generation production processes. The available resources for such processes are more limited than waste oils, and therefore supplies of waste-based first-generation ethanol tend to be limited (e.g. the UK consumes mostly waste-based biodiesel and mostly crop-based ethanol).

Adding a hydrolysis pre-treatment step allows the extraction of sugars from cellulosic and ligno-cellulosic material, which would greatly expand the potential pool of waste and residual resources for ethanol production. The major cellulosic resources include crop harvest residues and forestry residues, as well as cellulosic material in the biogenic fraction of MSW (cf. Searle & Malins, 2015). If cellulosic ethanol production technology could be successfully commercialised it would dramatically increase the potential for ethanol production from wastes and residues, but to date the industry has struggled to achieve successful production at commercial scale.

Ethanol cannot be used in aviation directly, but it is possible to synthesise jet fuel from ethanol using an ‘alcohol to jet’ (AtJ) technology. The economics of AtJ pathways may be challenging, however, and in particular it is unclear whether AtJ pathways from cellulosic resources could compete with thermo-chemical pathways for cellulosic jet fuel production (see below).

1.3.1 Gasification and Fischer-Tropsch fuel synthesis

An alternative pathway to produce hydrocarbon fuels from cellulosic wastes and residues is gasification followed by a fuel synthesis step such as the Fischer-Tropsch reaction. Gasification involves heating material to a high temperature in order to cause chemical breakdown into constituents including carbon monoxide and hydrogen. These are separated from gases containing any other trace elements, and then may be reacted together to reform larger molecules in a synthesis reaction such as methanol synthesis or Fischer-Tropsch synthesis to produce hydrocarbons.

With appropriate final upgrading steps (comparable to processes at conventional oil refineries) the Fischer-Tropsch process can be used to produce road fuels or aviation fuel.

1.3.2 Pyrolysis and upgrading

Pyrolysis is a reaction that occurs at lower temperatures than gasification, whereby the organic molecules in a feedstock are broken down to produce a solid fraction (char), liquid fraction (pyrolysis oil) and gaseous fraction (lighter molecules such as methane). The pyrolysis oil can be upgraded into hydrocarbon fuels by hydrotreating.

1.4 Waste and residual feedstocks in the RTFO

The UK is one of the nations that has taken concerns about indirect land use change most seriously in structuring its biofuel mandate, having responded to the 2008 Gallagher Review (RFA, 2008) by reducing the rate of increase of biofuel targets and introducing a valuable double counting incentive for the use of fuels from waste or residual feedstocks, with the result that the UK biodiesel supply is dominated by fuels from used cooking oil.

1.4.1 Biofuels

The UK DfT undertakes independent assessment of possible biofuel feedstocks to determine whether they should be categorised as products and single counted under the RTFO, as single counted wastes and processing residues, as double counted wastes and processing residues or as double counted agricultural residues. The DfT assessment is based on criteria similar to those considered by the European Commission in establishing whether feedstocks should be added to Annex IX of the RED, but applies a broader definition of which feedstocks are valuable enough to be treated as products. The current list of feedstocks is shown in Table 1.

Table 1 Feedstock categorisations under the RTFO[8]

Category	Material
Products	Acid ester
	Brown/sulphite liquor
	Corn or wheat dried distillers grain (DDGS)
	Corn oil
	Crude tall oil
	Glycerol (refined) from virgin oils
	Meal from virgin oil production
	Molasses
	Palm fatty acid distillate (PFAD)
	Palm kernel oil
	Palm oil olein
	Palm stearin
	Starch slurry regular
	Sugar beet pulp
	Tallow (animal fats from rendering) category 2
	Tallow (animal fats from rendering) category 3
	Tallow – unknown
	Uncategorised tallow
	Virgin oils
	Whole crop rye
Single counted wastes and processing residues	Draff
	Pot ale syrup
	Slaughter wastes (category 3)
	Spent wheat grains
Double counted wastes and processing residues	Brown grease
	Cashew nut shell liquid (CNSL)
	Category 1 and 2 farmed salmon oil
	Cobs from processing
	Crude glycerine
	Cuttings from invasive vegetation
	Empty palm fruit bunches
	Ethanol used in the cleaning or extraction of blood plasma
	Ethanol used in the extraction of ingredients from medicinal plants
	Food waste (unsuitable for animal feed)
	Grape marc and wine lees
	Manure

[8] https://www.gov.uk/government/publications/renewable-transport-fuel-obligation-rtfo-feedstock-materials-used-for-creating-renewable-fuels/rtfo-list-of-feedstocks-including-wastes-and-residues

	Municipal grass cuttings
	Organic municipal solid waste (MSW)
	Out of date disinfectant
	Palm oil mill effluent (POME)
	Pot ale
	Poultry feather acid oil
	Rapeseed residue
	Renewable component of end-of-life tyres
	Residues from cottage cheese and quark production, contaminated with disinfectants or flocculants
	Sewage sludge
	Soapstock acid oil contaminated with sulphur
	Spent bleaching earth
	Sugar beet betaine residue
	Sugar beet tops, tails, chips and process water
	Tall oil pitch
	Tallow (animal fats from rendering) category 1
	Unrefined liquid dextrose ultrafiltration retentate
	Used cooking oil (UCO)
	Waste pressings from the production of vegetable oils
	Waste slurry from the distillation of grain mixtures
	Waste starch slurry
	Waste wood
	Wet corn fibre
Double counted agricultural residues	Arboricultural residues
	Bagasse
	Cobs
	Forestry residues
	Husks
	Nut shells
	Straw

Waste and residual feedstocks are treated as having no emissions up to the point of collection under the RTFO[9], and there is no crediting of avoided emissions – for example, if biogenic material is diverted from landfill to fuel production the RTFO does not give any avoided methane production credit.

1.4.2 Recycled carbon fuels

RCFs have not yet been made eligible for support under the RTFO or SAF mandate proposals as adding non-renewable fuels would require new legislation, but the UK Government has indicated its intention to add them in due course. It has been indicated that RCFs would only

[9] And presumably assume also under a UK SAF mandate.

be considered in the development fuel category under the RTFO – i.e. only advanced fuels from designated wastes and residues that are not subject to the same blending limitations as ethanol and biodiesel (UK Department for Transport, 2021a) – and that in the first instance only fuels produced from refuse derived fuel[10] and industrial waste gases would be eligible.

[10] Refuse derived fuel is a product consisting of combustible components from municipal solid waste.

2 Waste emissions in GHG inventories

The IPCC's Guidelines for National Greenhouse Gas Inventories split emissions into five sectors: energy; industrial processes and product use; agriculture, forestry and other land use; waste; and other. The inventory for the waste sector should include emissions from: solid waste disposal; biological treatment of solid waste; incineration[11] and open burning of waste; wastewater treatment and discharge; and other.

Within the system of emissions inventories, it is clear that waste emissions relate to the final disposal of materials with no further use. The main sources of emissions in the waste sector inventory are:

1. Methane release from disposal of biodegradable solid waste to landfill, excluding methane recovered for energy generation or flaring;
2. Methane and nitrous oxide release associated with biological treatment of solid waste;
3. CO_2 and nitrous oxide emissions from combustion of waste without energy recovery (incineration or open burning) (excluding CO_2 emissions from combustion of biogenic waste);
4. Methane and/or nitrous oxide release associated with wastewater treatment.

2.1 Fossil carbon in waste

Under UNFCCC inventory rules, a CO_2 emission from fossil carbon is recorded if the fossil carbon is combusted or otherwise decomposed to CO_2 and released. In the case of fossil carbon in waste, the most likely routes for CO_2 emission are incineration without energy recovery for disposal, in which case the emissions are recorded in the waste inventory, and incineration with energy recovery, in which case the emissions are recorded in the energy inventory. In the UK, incineration without energy recovery was banned in 1996 (p135, Brown et al., 2022) and therefore all incineration emissions are reported in the energy inventory. We discuss further in the next section on biogenic carbon in waste (section 2.2) the issues that arise in relation to the use of estimation methods to establish the fossil and biogenic fractions in the waste stream.

2.1.1 Waste emissions under emission trading schemes

The production of heat and/or power from fossil fuel combustion in installations with power ratings of higher than 20 MW is normally regulated under the EU/UK ETS, but municipal waste incineration is currently exempted in both schemes. This means that operators of waste to energy plants are not required to purchase emissions allowances to offset the CO_2 emissions

[11] Not including incineration with energy recovery which is to be included in the energy sector inventory.

from the combustion of waste containing fossil carbon. The European Commission has been asked to report by 2026 on the inclusion of waste to energy installations in the EU ETS[12].

2.2 Biogenic carbon in waste

IPCC guidelines impose the convention that changes in carbon stock in the biosphere are assessed in the forestry and other land use part of the agriculture, forestry, and other land use sector; emissions from changes in biospheric carbon stock are also referred to as land use, land use change and forestry (LULUCF) emissions. This means that CO_2 emissions from decomposition or incineration of biogenic material are not included in the waste sector inventory, or in the case of combustion of biological waste for energy in the energy sector inventory (though emissions of biogenic carbon from energy generation can be reported as a memo item), as this would in theory result in double counting of those emissions.

Carbon stock changes in UK LULUCF inventory emissions[13] are not established by direct measurement of carbon fluxes, but through the use of estimation measures (Brown et al., 2022). Biomass carbon stock changes due to land use changes are estimated by reference to the area of land under each land use category (and by a matrix of data on annual changes between categories). Carbon stock changes on forest-, crop- and grassland can be further estimated by reference to management change. For cropland and grassland these changes are estimated based on agricultural survey data. For forestland, The UK uses a carbon stock and balance model maintained by Forest Research, which also estimates changes in the harvested wood products pool.

Because LULUCF emissions are estimated based on aggregate data, emissions in the LULUCF sector are insensitive to specific local changes in disposition of biogenic wastes. To give an illustrative (though not necessarily realistic) example, imagine that a company was created specialising in producing bioenergy from old wooden furniture. This company would acquire used furniture which would normally have been expected to either stay in use or be sent to landfill/incineration without energy recovery, and instead would burn it for energy. In the first instance, this would not result in any change in inventory emissions recorded in the LULUCF inventory, even though this business model had directly caused a reduction in total carbon stock in harvested wood products, because this business practice would not be reflected in the harvested wood product model being used. If this business model became increasingly normalised, however, the Forest Research carbon stock model could be updated by amending the expected lifetime of carbon storage in furniture, and this could eventually affect UK inventory emissions, but as this change would not be a direct response to the activity level of our hypothetical company from the company's point of view they are getting 'free carbon', i.e. there is no change in reportable inventory emissions directly caused by them increasing the amount of furniture they burn.

This disconnect between changes in the disposition of biogenic wastes and any resulting change in reported LULUCF inventory emissions applies across types of biogenic waste. For example, consider a second (perhaps more plausible) business model whereby a new

[12] https://waste-management-world.com/resource-use/wte-and-eu-ets-what-the-inclusion-means-for-the-industry/

[13] The details of the use of estimation approaches to LULUCF inventory accounting may vary between countries – here we refer to the UK practices detailed in Brown et al. (2022).

company is set up to collect agricultural residues for bioenergy use, leading to a change in practice where residues that would otherwise be left on the field are collected. The removal of material from the field could lead to reductions in the rate of soil carbon formation (though depending on the rate of removal and local conditions this is not inevitable) – but the UK inventory would only register that change as a result of changes in responses in future agricultural surveys, so again there is no direct link from the change in practice due to a specific business to a change in inventory emissions, so from the point of view of the operator this is also 'free carbon' in inventory terms.

While our hypothetical furniture-to-energy business would not cause any direct change in emissions reported in the LULUCF inventory, the change in the amount of furniture heading to landfill or incinerators could lead to changes in CO_2 (and other) emissions in the waste inventory. This might be slightly surprising given that the waste inventory is not supposed to include any CO_2 from decomposition or combustion of biogenic waste, but it is an outcome that arises from the interaction between reporting of total mass of waste shipments and the use of default assumptions on the composition of those waste shipments. This means that when we increase energy recovery from furniture there is a change in the total quantity of material going to landfill or to incinerators, but the assumption on the fraction of landfilled and incinerated material that is furniture does not change.

Assume that there is a 50:50 estimated split of fossil:biogenic content in waste, that our company consumes nine hundred tonnes of wooden furniture a year, and that the previous disposition of this material was split evenly between a third landfill, a third incineration with energy recovery and a third ongoing use. The change in ongoing use doesn't affect anything in the waste inventories, and we would see reductions by 300 tonnes a year in the reported quantity of material going to landfill and 300 tonnes a year in the reported quantity of material going to incineration. The inventory doesn't know that these 300 tonne reductions are comprised entirely of biogenic carbon, and so the inventory calculations will assume that half of the material (150 tonnes in each category) would have been fossil derived. The inventory therefore records a reduction by 150 tonnes in the amount of fossil material assumed to be incinerated and a corresponding reduction in incineration emissions. The inventory also underestimates the reduction in biogenic material going to landfill (the inventory assumes a reduction by 150 tonnes rather than the actual 300 tonnes) and may also incorrectly estimate the expected change in landfill methane emissions[14]. These deviations in the calculated inventory emissions would not be corrected until and unless assumptions on waste composition are updated. We therefore have the potential situation that the reduction in carbon storage in harvested wood products is not registered in the LULUCF sector, while a false reduction in incineration emissions would be registered in the waste sector – in short, the inventory system is not able to (nor designed to) accurately track shifts in biogenic carbon storage or emission associated with small changes in waste disposition and composition.

2.3 Scope 3 emissions in company reporting

The company reporting rules under the GHG Protocol call on companies to consider emissions from waste disposal under Scope 3. Three options are given to companies in assessing waste-

[14] The methane estimation will assume that biogenic content reduces by 150 tonnes rather than 300 tonnes, but furniture will decompose more slowly than some other biogenic material, so the real change in methane emissions would not be the same as from removing 300 tonnes of 'generic' biogenic material.

related emissions: they can be assessed based on Scope 1 and 2 data from a specific waste handling company; they can be assessed based on average emission factors for a specified waste type and type of disposal; or they can be assessed based on average emission factors for the relevant forms of disposal. Emissions from waste handling would include emissions from incineration without energy recovery of fossil material, methane emissions from biodegradable material in landfill, and operational emissions associated with waste handling plants.

In the case that a waste stream was despatched directly from a waste generating company to be used in a fuel production pathway, the Scope 3 emissions for the waste generating company could be adjusted. GHG Protocol accounting allows the use of the 'recycled content' method which allows double counting of emissions in recycling to be avoided by attributing the emissions from recycling to the company utilising the recycled material rather than the company generating the material to be recycled. Similarly, in the case of waste being incinerated with energy recovery the GHG protocol suggests that the emissions should be assigned to Scope 2 for the company consuming the energy produced[15], and not considered in Scope 3 for the company producing the waste. This means that under GHG Protocol rules if a waste generating company sends its waste to a fuel producer (either for biofuel or for recycled carbon fuel) it would be able to get rid of the waste handling emissions term from its Scope 3 emissions reporting.

[15] And of course as a Scope 1 emission for the company operating the incinerator.

3 Long-term UK waste policy

The waste hierarchy calls for avoidance of waste and recycling of waste to be prioritised over energy recovery from waste. The availability of waste resources for alternative fuel production will therefore be affected by the success (or lack thereof) of waste reduction and of recycling policy. In this chapter we briefly review waste strategy in the UK in order to draw conclusions about potential changes in the availability of waste resources in future. Waste policy is a devolved area in the UK, and therefore there are separate waste policies for the individual nations of the UK. Here we focus on English waste policy as it applies to by far the larger volumes of generated waste.

English waste strategy is set out by HM Government (2018) in the 'Resources and Waste Strategy' (henceforth RWS). The document states that England will, "become a world leader in using resources efficiently and reducing the amount of waste we create", delivering a 'more circular' economy.

3.1 Plastic waste

One potential feedstock for RCFs is plastic and rubber produced from fossil resources. The RWS calls for 'avoidable' plastic waste to be eliminated by 2042 and for all plastic packaging on the market to be recyclable, reusable or compostable by 2025. Any material that is reused or can be recycled should, in principle, not be available for biofuel production, and therefore if policy to reduce the generation of non-recyclable plastic waste is effective then this should affect the quantity of plastic material going to either landfill or incineration, reducing the total potential resource available for RCFs. The RWS draws attention to the 'UK Plastics Pact', which sets a target that by 2025 70% of plastics should be effectively recycled or composted.

3.1.1 Chemical recycling

Currently, when we talk about recycling plastics we generally refer to mechanical recycling, which denotes processes whereby the chemical composition of the plastic being recycled is not changed. Chemical recycling routes, by contrast, involve breaking the plastic molecules down into 'base chemical constituents' which can then be reconstituted either into similar or identical plastics to the original material or into different plastics. Chemical recycling has similarities to the thermochemical processes that can be used to produce fuels from plastic waste – indeed, the British Plastics Federation identifies gasification and pyrolysis as chemical recycling processes[16]. The RWS calls for 'difficult to recycle' plastics that cannot be recycled mechanically to be designed out of the system, but identifies chemical recycling as an intermediate option for plastics currently in use that cannot be economically recycled by mechanical means.

[16] https://www.bpf.co.uk/plastipedia/chemical-recycling-101.aspx

3.2 Food waste

The RWS identified total UK food waste in 2015 as 10.2 million tonnes, of which 7 million tonnes was generated by households, 2 million tonnes by manufacturing, 1 million tonnes in hospitality and a quarter of a million tonnes in retail. This does not include any food waste associated with agriculture, which could also be eligible for use as a feedstock under the RTFO and SAF mandate. Of the food waste generated by households, the RWS states that about 5 million tonnes is considered still to be edible. Food waste in municipal waste is a major source of landfill methane. Food waste is therefore identified as driving emissions both through the occurrence of methane generation in landfill and through extra food supply chain emissions from over-production.

It is also a potential feedstock for biofuel production, either through anaerobic digestion for biogas or through a more advanced waste to liquids technology. The RWS aims to eliminate food waste being sent to landfill by 2030, with the most important measure to achieve this being the roll out of more segregated food waste collection bins.

The RWS follows the waste hierarchy in identifying (in order of preference) avoidance, redistribution for human consumption, use as animal feed and anaerobic digestion as approaches to reduce food waste disposal. The Anaerobic Digestion Strategy (DEFRA & DECC, 2011) prioritises anaerobic digestion on the basis that it may deliver better environmental outcomes than composting of food waste. However, there is little agreement in the literature about whether composting or anaerobic digestion generally delivers the better overall outcome. Both approaches produce a fertilising output (compost and digestate respectively) while anaerobic digestion also produces biogas that can be used for energy. The assessment of which is environmentally preferable hinges on how one weights the energy output of the anaerobic digestion process and how one rates the environmental services provided by compost.

The RWS sets a food waste reduction target of 20% from 2015 to 2025, but notes that at the time, "Our determination to cut food waste has not been matched by progress, which in recent years has plateaued." Data from WRAP[17] suggests, however, that by 2018 some reductions in food waste rates were being achieved, identifying a 7% reduction in food waste from 2015 to 2018.

3.3 Other biodegradable waste

The RWS states that in 2016 about half of the waste sent to landfill in England was biodegradable (about 6 million tonnes of biodegradable waste). In addition to food waste this includes fractions of paper waste, garden waste, textiles and wood. Most of the carbon in these non-food materials is bound up in cellulosic and ligno-cellulosic material, and cannot readily be processed into energy using anaerobic digestion or first generation biofuel technologies. These materials have potential as feedstock for cellulosic biofuel production. The RWS does not introduce specific targets for this waste fraction, but calls for 65% of all municipal waste to be recycled by 2035 and no more than 10% to be sent to landfill. These

[17] https://wrap.org.uk/taking-action/food-drink/initiatives/courtauld-commitment/history-courtauld-commitment

targets would leave about 25% of the total 2035 municipal waste resource available for energy recovery.

In May 2023, the UK Government launched a call for evidence on options to deliver the 'near elimination' of biodegradable waste going to landfill, to be introduced by 2028 (UK DEFRA, 2023). The Climate Change Committee has identified food, garden waste, wood, paper and card, and textiles to be targeted as a priority for diversion from landfill, including by separated collection. The call for evidence identifies anaerobic digestion and recycling as non-landfill dispositions for this material, i.e. it does not identify other energy recovery as an option. If liquid biofuel production is considered less desirable than anaerobic digestion, then this would constrain the relevance of these resources as transport biofuel feedstocks.

3.4 Waste in the UK carbon budget

The UK sets five-year carbon budgets as part of its climate planning, which include targets for emissions from waste (UK Government, 2023). By 'carbon budget 6' (CB6, 2033-2037) emissions from waste are supposed to be halved compared to the current carbon budget 4 (CB4, 2023-2027). The classification of waste emissions in the carbon budget follows IPCC principles (i.e. waste to energy is in the energy sector not the waste sector, and any use of waste-based fuels in transport would be recorded as emissions in the transport sector under the UK inventory, or in the international aviation/shipping inventory for waste-based fuels used in international aviation of shipping applications)[18]. As incineration without energy recovery has been largely eliminated in the UK and emissions from incineration with energy recovery are counted in the energy sector, the main source of waste emissions in the UK carbon budget is methane production by biodegradable waste in landfill. Separate food waste collection is therefore a key waste-sector policy, alongside improved separation of other biodegradable materials for recycling. The plan anticipates further policy to deliver the "near elimination" of biodegradable waste to landfill. Other waste-related policies include 'packaging Extended Producer Responsibility' and a Deposit Return Scheme. These policies will reduce the amount of both fossil and biogenic waste going to landfill and to incineration with energy recovery, and this should make incineration capacity available for further landfill reduction. There are also various measures listed that are intended to reduce emissions from wastewater treatment.

In the energy from waste sector the carbon budget anticipates the deployment of CCS from the end of CB4. This would help to reduce energy sector emissions, but also would have implications for a displacement analysis comparing RCF production to incineration with energy recovery – if CCS on incinerators is widely deployed and is then made part of the counterfactual for RCFs then the relative GHG emission advantages of RCF production would be reduced or maybe even reversed.

In the LULUCF sector the plan identifies increased production of livestock feed from (unidentified) wastes as an emission reduction strategy – there is no discussion of how such uses could compete with the biofuel sector, which already uses some waste or residual materials that could potentially be used in livestock feed (such as glycerine and rendered animal fats).

[18] Though with CO_2 from combustion of SAF based on biogenic waste being counted as zero.

3.5 Energy from waste and the SAF mandate

The UK identifies energy from waste (i.e. incineration with energy recovery) as a key measure to avoid landfilling waste, though the 65% recycling target for municipal waste implies a reduction in the rate of energy recovery from waste. If waste reduction policy reduces total waste generation, then within this constraint reduced energy recovery would be a predictable consequence. The RWS notes that most UK energy from waste plants are not yet able to export heat, which reduces the achievable thermal efficiency of the facilities[19].

The RWS identifies the use of waste feedstocks under the RTFO as a success, notes the use of incentives to maximise the use of waste feedstocks under the RTFO, and mentions that the use of recycled carbon fuels under the RTFO was being considered (presumably including in aviation, though the introduction of a SAF mandate seems not to have been considered in the RWS). The RWS doesn't make any clear statement on the expected scale of transport fuel (or indeed aviation fuel) production as a waste utilisation option, but certainly makes no indication that the use of wastes for transport fuels should be reduced or eliminated.

[19] The RWS suggests a power-only efficiency of 27% and a CHP efficiency of 40%.

4 Wastes and residues in lifecycle analysis

In the lifecycle analysis of alternative fuels produced from primary resources (whether from crops or from electricity) it is normal to take into account the GHG intensity of the processes required to produce those resources. For biofuels, this means a consideration of emissions due to agricultural production and the production of agricultural inputs. For e-fuels this means a consideration of the emissions due to electricity production (including consideration of questions of additionality).

When wastes or residues are used as feedstock, however, it is not obvious that it is appropriate to treat those materials as 'responsible' for the emissions associated with their respective production systems. If we consume a tonne of natural gas to produce a tonne of product and a tonne of waste, how much of that natural gas use should be associated with the waste production? We could say that half of the gas was used to make the product and half to make the waste, but this seems wrong given that nobody wanted to make the waste in the first place. We need to decide on appropriate rules for what fraction (if any) of upstream emissions are allocated to co-products and to wastes and residues from a given process.

4.1 Allocations

As discussed in Part 1 of this series of papers, attributional lifecycle analysis (LCA) systems for fuel production require that we set allocation rules to decide what fraction of the emissions from a given process are assigned to each of the produced outputs. We discussed that common rules include allocation by mass, by energy or by value. For mass allocation in particular, however, it is often necessary to specify that some output will have no emissions allocated to them, as even though they may have considerable mass they may not be intended or valued products of the system. This is less of a concern when allocating by energy or by value as these systems of allocation tend to preclude the case that an unwanted product would receive a large fractional emissions allocation. Excluding some outputs from emissions allocations is an element of consequential thinking introduced in an attributional framework – it reflects the idea that the emissions from a given process are a 'consequence' of wanting to produce the higher value co-products, and are not affected by the incidental production of residues or wastes.

Regulatory LCA generally includes some basis whereby the outputs of a system can be divided into co-products to which some fraction of process emissions will be allocated, and other by-products to which no emissions will be allocated. Under the RED and RTFO, emissions from upstream processes are allocated only to outputs that are identified as co-products (on an energy basis), and "no [upstream] emissions shall be allocated to wastes and residues". Any emissions that occur later in the supply chain associated with pre-treatment, aggregation, transport and processing of the waste or residual material are still considered.

Exempting wastes and residues from allocation of upstream emissions gives them a favourable status in terms of the overall GHG intensity score awarded by the RED LCA. This means that biofuels from wastes and residues tend to easily meet the minimum GHG reduction thresholds set by the RED[20], and that they have an innate advantage in regulatory treatments where the compliance value of a fuel is proportional to its regulatory GHG intensity score, such as has been proposed for the UK SAF mandate, and is active in the RED implementations in Germany and Sweden, and under the California Low Carbon Fuel Standard.

4.2 Existing use and indirect effects

While attributional LCA approaches tend to be very favourable to fuels produced from wastes and residues, consequential thinking reveals that attributional approaches may not give a meaningful sense of the overall net GHG implications. To illustrate the point, we can consider a simple (and real) example.

Consider a rendering plant at which the carcasses of livestock animals are processed once they have been stripped of meat and saleable fat. Such plants use heat to simultaneously sterilise the remaining material on carcasses and to separate fatty material from protein-rich material, producing both rendered animal fats and protein meals. The rendered animal fats have had various historical uses, including soap making, animal feed, and oleochemicals, and the lower quality rendered fats[21] would often be combusted on site to provide heat for the rendering process (Malins, 2017a).

With the growth of the biofuel industry a new option for rendered animal fats became available, and low-quality fats started to get displaced out of the existing bioenergy application (process heat) and into an alternative bioenergy application (transport fuel). A report for UK Department for Transport by AEA Energy & Environment (2008) used a simple consequential LCA analysis to flag the concern that while biodiesel from these animal fats could displace the use of road diesel in the transport sector, the animal fats previously used for on-site heat and/or power would simultaneously need to be replaced with an alternative fuel such as fuel oil. As the GHG intensity of fuel oil is similar to that of road diesel, there would be little if any net climate benefit from this shuffling of fuel use.

In this example, a simple consequential analysis calls into question whether the increased use of low-quality animal fats for biofuel would deliver any net GHG benefit compared to the existing energy use. In that case, why should policy provide incentives to turn that feedstock into biofuel?

The answer to this may depend on how each new policy balances the desire to deliver net GHG reductions with the desire to avoid making direct prescriptions about how specific resources should be used. Clearly the overall goal of climate change mitigation policy is to drive changes in corporate or individual behaviour and practice that deliver net GHG reductions. From that point of view, any policy that simply shuffles emissions between sectors without delivering a net benefit doesn't look like a good policy. In this case the outcome emerges, however, from a combination of inventory thinking and the imposition of market-based requirements, which may both seem like appropriate policy choices in their own right.

[20] In principle it is possible for a biofuel from a waste or residue to still fail against the threshold because of an energy intensive production process or high emissions from aggregation and transport, but these cases would be an exception.

[21] Rendered animal fats are split between lower quality material in Categories 1 & 2 which is almost always combusted for energy recovery, and higher quality material in Category 3 which is generally used in animal food or oleochemical applications.

The logic being applied in policy is that if energy recovery from animal fats can displace fossil energy use, it is fine to set targets for renewables in both sectors and then to let the market determine which of the sectors represents the higher-value use. Even if the specific decision to move a batch of animal fat from a stationary use to a transport use seems to deliver no benefit, the policy logic is that if these choices are part of a working portfolio of policies that deliver on the Government's climate targets then that is more important than this specific example of a shuffling effect.

Allowing the nominal climate benefit of a renewable resource to be counted by whichever sector ends up using it is consistent with standard practices in inventory accounting. There are analogous issues in any market-based mechanism. For example, in biofuel mandates it is normal to count the consumption of imported biofuels as delivering emission reductions in the importing country. This is regardless of whether there is evidence that those biofuels would otherwise have been consumed in their country of origin. Within a single country, we might say that it doesn't matter which economic operator supplies the available quantities of biofuel, but in market-based biofuel mandate systems we still give credit to the operators that supply them and penalise companies that do not. The intention of such a biofuel mandate is that through this combination of credit and/or penalisation the system can drive increased overall levels of biofuel supply, even if at the level of an individual batch it may not seem to matter who the fuel is supplied by and to.

In the case of our animal fat example in the UK, if the animal fats are used for on-site energy by a rendering plant operator then this can deliver benefits under the UK ETS (BEIS, 2021). If the animal fat is transferred to the transport sector as biodiesel, then instead the transport fuel supplier accrues benefits under the RTFO. When the benefits of this renewable energy application disappear from the ETS, then other emission savings would need to be found in order to maintain the same overall compliance with ETS targets (this idea of 'policy-mediated' indirect effects is discussed by Malins, 2017a). If the relative value of emissions reductions in the two sectors has been appropriately set by policy, then these market choices should deliver the 'best' net outcome. In the transport sector, emissions reductions with biofuel are given a higher implied carbon price in policy than emissions reductions in ETS, and therefore within that pricing system it is logical to transfer the reportable benefits of animal fat use to the transport sector and to find other emissions reduction options to make up the ETS deficit. This will be cheaper than it would be to keep using the animal fats in stationary applications and to find alternative biofuels for transport use. If this price hierarchy were to change, then we would expect the market to start moving animal fats back into stationary applications.

On its own terms, the logic of these policy choices is sound – but the logic may start to break down if applied in certain contexts. In a case where a bioresource is transferred from a sector or country where it is used for renewable energy but GHG emissions are unregulated into a sector or country where GHG emissions reductions have a defined value, then there is no reason to expect a compensating emission saving in the original sector/country. For example, it is our understanding that in the UK rendering plants would only be regulated under the ETS if they had combustion units onsite with a combined thermal rating of 20 MW or more. Smaller rendering facilities would not be regulated, and thus there would be no loss of ETS value if animal fats were displaced from such smaller facilities[22].

[22] We do not have data on the actual typical thermal capacities at UK rendering plants – at this point the example is in any case moot as we understand that the use of animal fats for power at rendering plants has already been more or less eliminated in favour of biofuel production (Malins, 2023).

What's more, the decision making under this sort of policy combination will only be rational to the extent that the difference in the value of savings ascribed to the different sectors is appropriately set. If the value given to emission reduction in the transport sector is three times the value given in stationary applications, then it would be rational to use the animal fats in transport even if transport use only delivered half as much CO_2 benefit as using animal fats in heat and power. There is no simple 'correct' answer to this question. Often, offering a higher carbon price in one application than another can be justified with reference to longer-term concerns. If we strongly believe that a technology will be needed in 2050 in a net zero world, then we might argue that it is worth offering that technology a higher carbon price now in order to accelerate its development, enabling greater carbon savings to be achieved in the long run. In transport, an argument of this sort is often applied with reference to alternative aviation fuels. If our 2050 net zero scenarios require alternative aviation fuels, then the logic goes that we can justify spending more on GHG reduction from those fuels today because it would be impossible to fully scale up an alternative aviation fuel industry in a shorter time. The validity of these arguments is at least somewhat subjective, but they are legitimate arguments to make. In the specific case of animal fats for alternative aviation fuel, these types of arguments may represent a sort of category error – because the supply of animal fats and vegetable oils is limited, even though we may believe we need to scale up alternative aviation fuel consumption by 2050 we know that lipid hydrotreating will not be a key technology in that timeframe, so the long-term utility of using animal fats in aviation fuel now is unclear at best.

Stepping back again, even if we can find individual examples where this combination of inventory thinking and value hierarchies leads to results that may not deliver either net GHG benefits or necessary technology development, a policy maker might argue that it is still worth sticking to the principle that the benefit of biomass use for energy is attributed to the owner at the point of use providing there are other cases where the outcomes are more positive. They might argue that doing so allows them to keep the regulatory system simple and to give demonstrably consistent treatment between different resources. In the context of the energy transition, the policy maker might further argue that eventually a larger and larger share of GHG emissions will be regulated under some sort of inventory system, and that the number of cases where resource shuffling delivers zero net benefit will correspondingly shrink.

Such arguments may have some merit when applied across energy applications, but are harder to justify when we consider cases of displacing resources out of non-energy uses. Going back to AEA Energy & Environment (2008), another displacement option was suggested alongside the possibility of displacement of animal fats out of existing energy recovery. In the case of animal fats used in soap making and oleochemicals, AEA identified palm oil as a likely substitute. More recent studies of animal fat displacement note that because stationary applications have been almost eliminated in Europe by now, palm oil is probably the main replacement material if ever more animal fats are drawn into biofuel use (Malins, 2023). We know that additional palm oil production is associated with agricultural emissions, and that palm oil expansion is linked to deforestation and peat drainage, leading to significant ILUC emissions as well (Malins, 2019). It is ironic to offer incentives to shift ever larger volumes of high-quality animal fats into biofuel use, thereby increasing palm oil demand and likely increasing net GHG emissions, at the same time as removing incentives for the direct use of palm oil in biofuels. Nevertheless, the REFuelEU aviation fuel mandate will offer support for the use of all animal fats as feedstocks, although note that feedstocks not listed in Annex IX of the RED are capped at 3% of aviation energy.

One way to address these issues in policy would be to add a term for indirect emissions from feedstock displacement in the LCA for these fuels. This would reduce the advantage given to feedstocks such as animal fats in GHG-based regulatory systems. Such a term was suggested for feedstocks including Category 3 animal fats in a recent European Commission proposal for amendments to the RED but was rejected in the final text. It should be noted that the RED doesn't entirely ignore these issues – while displacement emissions are not part of the regulatory LCA framework, the consideration of 'market distortions' is part of the assessment when new feedstocks are considered for addition to the list of wastes and residues[23] in Annex IX of the Directive. A recent assessment suggested that several materials may not be suitable for inclusion in Annex IX for these reasons (Haye et al., 2021). This shows that it is possible to include these consequential considerations of displacement emissions within the policy process even if the displacement emissions are not included directly in the regulatory LCA framework. The Directive does not, however, provide for reassessment of substances already on the list – so in the case of Category 1 and 2 animal fats inclusion was settled several years earlier through the political process of developing the text of the Directive, rather than in reference to a specific technical analysis that considered potential market distortions.

4.3 Existing disposition

In some cases, a waste material has no existing use but instead has some form of existing disposition, and this disposition may itself be associated with GHG emissions (or, more rarely, with a GHG sink). A good example of this is food waste. In the UK, a significant fraction of food waste ends up in residual municipal waste, some of which is landfilled. When food waste is landfilled it will start to decompose, either aerobically leading to CO_2 production or anaerobically leading to methane production. Produced CO_2 is treated as a zero emission in inventory accounting because it is biogenic, but methane from food waste is counted as a GHG emission in the waste sector inventory. If food waste can be used as biofuel feedstock instead of going to landfill, then that methane emission can be avoided, and therefore a consequential LCA could assign an emission credit to a biofuel process for using the food waste (i.e. it would enter the LCA system with negative embedded emissions).

A slightly more involved case arises with fossil waste that would have been incinerated with energy recovery (if we treat this as a form of disposal rather than a form of use – but the consequential analysis is the same either way). Here there is an avoided emission as the waste is no longer combusted at an energy from waste plant, but this leads to a reduction in energy generation. A full consequential analysis would therefore also have to consider whether additional emissions would be incurred to replace that lost energy generation.

Finally, consider a case that could be associated with a GHG sink rather than a source. When agricultural residues are disposed of by leaving them in the field, some of the carbon in the material may end up getting incorporated into the land as additional soil carbon. In that case, we might assign a positive GHG intensity for lost carbon sequestration when those residues are used as feedstock (although as soil carbon formation is a complicated and location/management specific process, it may be difficult to establish with precision what this GHG intensity should be).

[23] Note that this list is not strictly limited to wastes and residues, but that in practice most listed materials are wastes or residues.

4.3.1 Existing disposition and long-term biogenic carbon

A particular case arises when a waste or residual material contains biogenic carbon and would normally be disposed of without destruction (i.e. to landfill or left in place in an agricultural or forestry context). Examples of this would include stumps left in commercial forest after timber harvesting, large branches left after timber harvesting, construction timber sent to landfill, and bioplastics that are either non-biodegradable or that biodegrade only very slowly in ambient conditions. Whereas materials like agricultural residues and food waste decompose relatively quickly in natural conditions, longer lasting materials could remain at least partly intact for decades depending on climate and weather conditions.

Under the UNFCCC convention of treating biogenic carbon emissions as zero in industrial inventories, we would not draw any distinction between whether this carbon remained in place for a hundred years or was immediately combusted for energy. In reality, however, this does make a difference – keeping carbon stored in biomass means it is not in the atmosphere heating the planet (see also Part 1 of this series of reports). If carbon can be stored in biomass on a decadal timescale, this can make a significant climate difference.

As it stands regulatory LCA systems for biofuels do not draw any distinction between the treatment of wastes and residual feedstocks that would have decomposed quickly versus the treatment of materials with medium- or long-term carbon storage potential, although sustainability rules can preclude the use of some resources such as roundwood. The carbon debt associated with increased harvesting of forestry system and the combustion of large woody debris has been extensively discussed (Baral & Malins, 2014), but the RED/RTFO LCA treatments do not distinguish them.

While the LCA does not address these issues, there is some implicit recognition of carbon debt in the sustainability requirements placed on feedstocks under the RED. There is a prohibition on using saw logs for biofuel feedstock, and there is a requirement that biomass harvesting from forest areas should be done in a way that maintains soil quality and biodiversity – this criterion ought to restrict stump harvesting.

4.4 Analysing displacement emissions

While it is possible to let concerns about displacement emissions inform decision making without making them part of the regulatory LCA, various efforts have also been undertaken to provide indirect emissions estimates for a range of wastes and residues, and to develop methodologies to take them into account. These indirect approaches are all based on some variation of the following approach:

1. Identify existing use(s) and/or disposition(s)[24] of the material in question;
2. In the case of existing use(s):
    a. Identify likely replacement materials after displacement;

[24] For the sake of this outline methodology, assume that any form of energy recovery is treated as a use.

   b. Establish GHG intensity values for these materials. In the case of materials that are themselves wastes or residues this may require applying the methodology recursively;

   c. Estimate the replacement share for each replacement material;

   d. Calculate a replacement GHG intensity as the product of the GHG intensities and replacement shares.

3. In the case of existing disposition(s):

   a. Establish a GHG intensity of disposition based on any GHG emissions or sequestration associated with that form of disposition;

   b. Estimate the disposition fraction for each method of disposition;

   c. Calculate a disposition GHG intensity as the product of the GHG intensities and disposition shares.

Examples of this type of assessment are available in Brander et al. (2009) and Malins (2017a).

4.4.1 Rigid input methodology (IF, RCF, RFONBO)

While the analysis of displacement emissions has not been integrated into the LCA for biofuels under the RED/RTFO, a similar approach has been implemented in the LCA requirements of the EU Innovation Fund (European Commission, 2021) and in the RED LCA requirements for RCFs and e-fuels (European Union, 2023) through the idea of 'elastic inputs' and 'rigid inputs'. In these rules, elastic inputs are defined as those whose supply may be increased in response to extra demand, while rigid inputs are those whose supply is unresponsive to demand. These ideas echo the distinction between co-products as intended outputs from a process where an increase in demands for the co-product would lead to increased use of the process, versus residues and wastes as unintended outputs whose rate of production is independent of any level of demand for them. The threshold set for rigid inputs in the LCA for RCFs and e-fuels is 10% of the economic value of all the outputs of a process. Emissions associated with inputs deemed to have elastic demand are assessed as normal for attributional analysis, but emissions associated with rigid inputs are determined entirely by identifying diversion emissions from alternative use or disposition.

In the particular case of MSW used as an input for a fuel production process, the EU Innovation Fund provides a generous treatment in the LCA by allowing applicants to treat any waste that would normally be landfilled as if it would have been incinerated without energy recovery. This results in an avoided emissions credit even if no emissions have actually been avoided – the underlying logic being that as landfill is to be discouraged, there should be no carbon benefit assigned to landfilling waste instead of incinerating it. The Innovation Fund is also generous when the alternative disposition would have been power generation, as it allows applicants to treat displaced power generation as zero emissions. These methodological choices result in municipal waste (and other fossil waste streams that would normally be combusted for power generation) being treated as a sort of carbon free resource in the Innovation Fund.

4.4.2 Method proposed for the RTFO

The UK Government consultation on making RCFs eligible under the RTFO (UK Department for Transport, 2021b) suggests a similar approach to the 'rigid inputs' rules adopted in the EU. The proposed formula for the total emissions per unit of fuel is:

$$E = E_{\mathrm{prod}} + E_{\mathrm{td}} + E_{\mathrm{disp}} - E_{\mathrm{CCS}}$$

where:

- E_{prod} is emissions from fuel production;
- E_{td} is emissions from transport and distribution;
- E_{disp} is emissions from displaced energy use; and
- E_{CCS} is emissions saving from any implementation of carbon capture and storage.

The proposal is that the displacement term would by default be based on incineration of the waste feedstock for electricity production with a thermal energy efficiency of 26%, and that the GHG intensity assumed for the displaced electricity should be the average GHG intensity for electricity produced in the relevant country in the previous year. As it is expected that grid electricity will be gradually decarbonised in most countries due to the energy transition, this means that reportable GHG emission reductions from the use of RCFs would gradually increase over time – and DfT has therefore proposed that the minimum reportable GHG savings threshold for RCFs should also increase over time.

4.4.3 Counterfactual example – RCF from the fossil component of RDF

To illustrate the importance of counterfactual assumptions for rigid inputs, let us consider the case of a technology to produce an RCF for transport by gasifying the fossil component of refuse derived fuel and using Fischer-Tropsch hydrocarbon synthesis with an overall energy conversion efficiency of 50%. Assume that the GHG intensity associated with the gasification and fuel synthesis is 15 gCO_2e/MJ calculated on an attributional basis, and there are a further 5 gCO_2e/MJ of emissions associated with transport and distribution of the inputs and produced fuel. The feedstock is assigned zero production emissions up to the point of collection, but because the carbon in the RCF is of fossil origin, the emission from combustion of the fuel should also be counted – that's another 73 gCO_2e/MJ so the total attributional 'direct' emissions for the pathway are 93 gCO_2e/MJ. This is about the same as the fossil comparator GHG intensity value used in the RED and RTFO, which is 94 gCO_2e/MJ. But what are the 'indirect' emissions associated with the RDF as a rigid input? We can produce illustrative hybrid LCA results with three different counterfactuals on the RDF disposition:

1. The RDF would otherwise be incinerated without energy recovery;

In this case, we assume that in the absence of RCF production the material would have been burnt anyway, so there is a negative emission term for avoided CO_2 release. For simplicity we can assume that the amount of carbon in the RDF is exactly the same as in the produced RCF (i.e. total conversion of carbon into fuel molecules) so the combustion emissions credit is the same as for combusting the fuel – 73 gCO_2e/MJ (in this case this is again expressed per MJ of energy in the fuel, which could be different than per MJ of feedstock). This exactly cancels out the fuel combustion emissions, leaving a total hybrid LCA score of 20 gCO_2e/MJ, for a reportable GHG saving of 79%[25].

2. The RDF would otherwise be incinerated with energy recovery;

In this case we have the same avoided combustion of the RDF, but there is also a lost electricity generation term. If the electricity generation from RDF is 26%, then we will lose 0.52 MJ of electricity generation for every MJ of FT fuel produced. UK electricity generation has an average GHG intensity of about 180 gCO_2e/kWh[26], equivalent to 51 gCO_2e/MJ. If we take that average GHG intensity as representative of the GHG intensity of the electricity that would be generated to replace lost energy from waste, then replacing 0.52 MJ of electricity would be associated with 26 gCO_2e, giving a total hybrid LCA score of 46 gCO_2e/MJ, a 51% reportable GHG saving.

3. The RDF would otherwise be landfilled;

In this case there is no avoided combustion of RDF as it would otherwise have been landfilled, so there is no credit for avoided emissions and the hybrid LCA score is 93 gCO_2e/MJ, a 1% reportable GHG saving.

We see therefore that an otherwise identical RCF production pathway could be assigned a reportable GHG saving anywhere from 1% to 79% depending on the counterfactual assumptions applied to the RDF as rigid input.

4.5 Avoided emissions credits in CORSIA

ICAO's CORSIA mechanism currently allows for avoided emission credits to be registered for two waste-based fuel pathways. The first is a methane avoidance credit for alternative aviation fuel produced from municipal solid waste that contains biogenic material. The credit is based on the estimated methane production had the feedstock been landfilled. The second is a credit for increased recycling for alternative aviation fuel produced from municipal solid waste where it is claimed that feedstock preparation supports the recovery of additional material for recycling.

4.6 Falling through the inventory cracks?

Comparing GHG inventory approaches for wastes to proposed consequentially-informed LCA approaches for waste-based-fuels, it becomes apparent that there is some risk that the emissions from combustion of fossil carbon in wastes could 'disappear' from GHG inventories.

Consider a company currently sending a quantity of non-biodegradable non-recyclable plastic waste for disposal in landfill. The company would not be expected to report any Scope 3 emissions for the carbon in the plastic for this form of disposal as the carbon in the waste is not released, nor would the carbon in the plastic be reflected in a national GHG inventory as

[25] The issues around calculating GHG saving score sin this way are discussed in Part 1, but here we present the result as it would be presented in the regulatory LCA framework.

[26] https://www.nationalgrideso.com/news/britains-electricity-explained-2022-review

it is effectively in long-term storage in the landfill. What happens if this plastic stream is now instead sent to an RCF producer[27]? The waste generating company would still not be expected to report any emissions for the carbon in the plastic in its Scope 3 emissions as the GHG Protocol makes it clear that the consumer of the energy product should account for the emissions from the combustion. Under the proposed UK RTFO/SAF rules for LCA of RCFs[28], the user of the fuel would calculate GHG emissions based on a displacement approach. The UK Government argues that landfill should not be considered as a counterfactual because it aims to largely eliminate landfilling, and so the displacement analysis would assume that the plastic would have been combusted for energy recovery if it had not been used for RCF production. In this treatment, the GHG emissions from RCF combustion are notionally cancelled out against the counterfactual emissions from waste incineration for energy. The emissions intensity ascribed to the RCF is then determined solely by the energy intensity of the RCF production process and by the GHG intensity assigned to the lost electricity production. The lower the GHG intensity of electricity, the lower the displacement emissions that are assigned to the RCF. Under the more favourable rules of the EU Innovation Fund, an RCF producer is not even asked to consider any emissions from electricity displacement.

Based on the combination of the accounting approaches from the GHG protocol and either the UK RTFO/SAF mandate or EU Innovation Fund LCA rules for fuels, neither the waste generator nor the RCF producer/consumer would account for the physical CO_2 emissions associated with combustion of the carbon from the plastic waste – i.e. this CO_2 emission would have 'disappeared' from the accounting system, at the company level at least. The physical CO_2 emission from the RCF use may still in principle be captured in the national inventory in the transport sector, and therefore the physical CO_2 from RCF combustion may at least still be tracked in national inventory accounting.

An inventory discontinuity is not, in and of itself, proof that the GHG accounting systems are not appropriate. GHG inventories are useful insofar as they enable monitoring and reduction of GHG emissions, but it is normal that there are inconsistencies between inventory and LCA approaches to GHG accounting because the scopes of the systems differ.

In the case of the treatment of landfill, however, there appears to be a risk that a climate change policy measure will effectively be used to implement a waste management policy decision. The UK RCF accounting rules are predicated on the idea that landfilling will be all but eliminated in the coming years because landfilling is considered environmentally problematic. However, if one mechanism used to eliminate landfilling is the promotion of RCF production there is a form of circular reasoning in effect.

With a longer-term view, it would seem reasonable to demand that the physical CO_2 emissions released by fossil waste combustion should be assigned to at least one company in the system. Currently, the GHG Protocol makes energy consumers responsible for the emissions from waste to energy facilities, but in an increasingly decarbonised grid where the likely alternative to energy from waste would be additional renewables this treatment may no longer seem appropriate. Requiring companies to report and take responsibility for the carbon in generated waste could be a useful step as part of a broader portfolio of policies intended to drive reductions in waste generation, and is consistent with the philosophy of 'extended

[27] In the proposed UK RCF rules it would be necessary for the plastic to first be aggregated into a refuse derived fuel product – this doesn't change the underlying carbon tracking.

[28] With apologies for the string of initialisms!

producer responsibility'[29]. Assigning responsibility for carbon in wastes is somewhat analogous to the question of assigning credit for CO_2 capture between CO_2 generators and e-fuels producers (Malins, 2017b). Just as it is not appropriate for two parties in the e-fuel production chain to claim the same credit from capturing CO_2, so it is not appropriate if no party in an RCF production chain is held accountable for the associated CO_2 emissions. Revising the convention in the GHG Protocol would be a start to ensuring that someone is asked to take responsibility for the CO_2 emissions associated with ongoing production and combustion of fossil wastes, and would ensure the maintenance of an incentive to avoid creating waste in the first place.

[29] https://www.gov.uk/guidance/packaging-waste-prepare-for-extended-producer-responsibility

5 Future counterfactuals

The UK energy transition is a long-term transition, intended to deliver net zero GHG emissions by 2050. In that context, it is important that the climate mitigation options that are supported are consistent with reduced GHG emissions not only in the short term but also in the longer term. This idea of temporality is particularly important when we consider assessing alternative fuel pathways using consequential thinking, as the consequences of changing the production and disposition of a given resource are likely to change over time. In the specific context of alternative fuels, we have already mentioned areas of policy in which elements of future thinking have been adopted in relation to LCA. We mentioned that in the EU Innovation Fund applicants are to assume that the electricity grid is already decarbonised when assessing their projects. We mentioned that in the UK's proposed RCF rules the near-elimination of landfilling is pre-empted by discounting landfill as a counterfactual for waste disposition. In this section we briefly discuss what might be taken as reasonable future counterfactuals for potential alternative fuel feedstocks, and uncertainties in identifying those counterfactuals.

5.1 Biogenic fraction of municipal waste

UK climate policy calls for the near elimination of biodegradable material from landfill waste, which implies the drastic reduction of methane emissions from landfill. If this is delivered, then developing new technologies to produce biofuel from municipal waste would have minimal impact on methane emissions – this would not change the LCA treatment under the RTFO, however, as avoided methane is not currently credited. Following the elimination of landfilling, all biodegradable waste must be either recycled (including composting[30]) or used for some form of energy recovery (one would hope that the total production of biodegradable waste would also be reduced).

The appropriate long-term counterfactual when utilising the biogenic fraction of MSW as biofuel feedstock would then be either incineration with energy recovery, anaerobic digestion for biogas, or composting. Anaerobic digestion and composting are considered higher on the waste hierarchy than other forms of energy recovery (they are treated as forms of recycling), but the waste hierarchy allows for some flexibility if the environmental benefits of a 'lower' disposition are considered greater.

5.2 Fossil fraction of municipal waste

UK policy is to reduce the total amount of waste going to landfill but not necessarily to eliminate landfilling, in the medium term at least. Landfill and energy recovery are therefore both potential dispositions for fossil carbon in waste. More generally, UK policy anticipates reducing the quantities of plastics that will be landfilled or incinerated by eliminating 'avoidable' plastic waste, including by ensuring that all plastic packaging is recyclable,

[30] Composting is an aerobic process and therefore is not associated with significant methane emissions if properly managed.

reusable or compostable by 2025, and anticipates that reductions in total waste volume will allow a reduction in landfilling by freeing up incineration capacity.

The proposed RTFO approach for establishing a counterfactual on the use of fossil waste for RCF production discounts landfilling as an option on the basis that "there are targets to reduce this significantly over the next decade, which may lead to the diversion of around 5 Mt of RCF feedstocks from landfill". The conceptual problem with this reasoning is that the UK Government also explicitly identifies RCF production as a route to "support tightening targets to reduce landfill and increase recycling". It is possible to draw two quite different counter-factual assumptions from these two statements.

The RTFO proposal implicitly assumes that if RCF production was not available as a route to reduce landfilling then energy from waste would have to expand instead in order to meet government objectives. In this view, even though RCF production is characterised as a way to reduce landfilling, the true counterfactual is an expansion of energy from waste – landfilling will be reduced at the same rate either way.

The alternative view would focus on the fact that while the UK Government has clearly indicated the intention of reducing landfilling, there are (to the best of our understanding) no firm targets and certainly no binding targets for reducing the amount of fossil waste sent to landfill. Rather landfilling is treated as a residual option that will naturally decline as rates of waste generation decrease and recycling and energy recovery increase. Within this understanding, it is not obvious that energy from waste capacity would expand faster if RCF deployment was slower or failed entirely. In that case the appropriate medium-term counterfactual for RCF production would include landfilling and would arguably be landfilling only (as it is the intention of the government that RCF does not compete with energy from waste but helps to reduce landfill rates). From a GHG emissions perspective, displacing fossil waste from landfill into energy recovery does not deliver any net benefit. It allows reductions in fossil fuel use but in doing so it releases CO_2 from carbon that would otherwise have been stored in landfill (this is why energy from waste is included as an emission term in the national GHG inventory). We accept that landfill reduction is a legitimate policy goal in and of itself, but we note that reducing landfilling does not necessarily deliver GHG co-benefits (although in the near term an argument can be made that support for RCF production could incidentally support the reduction of biodegradable material going to landfill by allowing co-processing of the fossil and biogenic components of MSW, and thereby reduce methane emissions).

There is an argument to be made that the UK Government is conflating climate policy with landfill reduction policy by seeking to treat fossil waste as a low-carbon resource available for RCF production. By this we mean that a value signal will be applied to encourage RCF use that is based on the carbon price for transport decarbonisation (the RTFO has an implied carbon price in the region of £200-300 per tonne of CO_2 abated), when it can be argued that the environmental benefit that is delivered by RCF expansion is landfill reduction not climate change mitigation. By applying a climate change incentive to a waste problem, the UK would effectively be distorting the playing field for landfill reduction strategies – the value of the RTFO incentive will be rather more than the disbenefit associated with landfill fees.

This counterfactual is clearly sensitive to the associated waste policy landscape. If the UK Government were to ban landfilling tomorrow, then incineration with energy recovery would indeed become the appropriate counterfactual. A greyer area arises if the government is able to avoid introducing an explicit landfill ban precisely because the combination of increased recycling, energy from waste and RCFs is expected more or less to eliminate landfilling through market incentives. In that scenario it may still be justified to treat incineration with energy recovery as the long-term counterfactual.

Overall, it is the opinion of the author that ignoring landfill in the counterfactual overstates the climate performance of RCFs from municipal waste in the short to medium term, but that it is less clear what the 'true' counterfactual should be in the long term. This means that if RCFs are made eligible for support under the RTFO in the near future the net GHG benefits of their use are likely to be exaggerated, and there is a risk that this could distort the allocation of incentives. To the extent that RCF production is used for RTFO compliance in preference to fuels with greater true net climate benefit, this could marginally reduce the climate benefit from the policy as a whole.

5.3 Agricultural and forestry waste and residues

In this report we have focused on municipal waste, but wastes and residues from agriculture and forestry are also potentially important biofuel feedstocks – indeed, in the long term these materials are likely to continue to be produced in large quantities even as municipal waste generation is supposed to be cut down. Disposition of these materials is currently varied, depending on the exact characteristics of the material and on local regional markets. For example, Searle & Malins (2013) identifies a number of existing uses for agricultural crop residues that vary across the EU.

If these residues are displaced from productive existing uses, then the proper counterfactual would include displacement emissions from sourcing alternative materials. Similarly, if the rate of residue extraction is so great that it interferes with soil carbon formation or with other ecosystem services then the counterfactual would include reduced soil carbon. In much of the discourse of agricultural and forestry residues as biofuel feedstock the focus has therefore been on identifying the fraction of material that could be utilised without significantly impacting other markets or ecosystem services, and treating this as the 'sustainably available' potential. If operators only extract this sustainably available potential, then the counterfactual would be that the material should be left in place and would gradually decompose releasing its carbon to the atmosphere as CO_2. In the case of woody residues in forestry we might add the condition of not significantly reducing carbon stock in dead wood. This could include restrictions on the use of large woody debris that would be likely to take many years to decompose – although the definition of what can and can't be sustainably utilised remains contentious in this case.

In the absence of firm sustainability requirements, establishing the appropriate counterfactual for removal of a given residue would require consideration of local conditions and of any economic disadvantage likely to result from over-harvesting of residues, but the counterfactual is likely to include some level of reduced carbon stocks or increased emissions from existing users.

5.4 Waste, residual and low value vegetable oils

The only alternative aviation fuel pathway that is currently operative at commercial scale is renewable jet fuel from vegetable oil hydrotreating, and this pathway requires vegetable oils (or animal fats) as feedstocks. In the aviation sector there will therefore be particular interest paid to opportunities to produce fuel from by-product oils. Because oils and fats are energy dense, few by-product oils are true wastes in the sense of the Waste Framework Directive. Wherever oils or fats are produced in significant quantities as industrial by-products they tend to be utilised – if there are no higher value applications they will be used as fuel (for example low quality animal fats being used as fuel at rendering plants) because they represent an alternative to the use of fuel oil or natural gas. The possibility of energy recovery means that the price of fuel oil sets a floor on the value of segregated oils and fats, but in many cases by-product oils and fats have significantly higher value applications, for example the use of category 3 animal fats in oleochemicals or refining tall oil from paper pulping (Malins, 2017a).

The relatively high value of many by-product oils is recognised under the RTFO by identifying them as products rather than residues. Examples include category 2 and 3 animal fats, palm fatty acid distillates, crude tall oil and distillers' corn oil. The counterfactual to the use of any of these materials would be other economically valuable uses, which in several cases may be at least as sustainable as use in aviation fuel.

The oily feedstocks that *are* identified as wastes or residues are used cooking oil, poultry feather acid oil, rapeseed distillation residue, sulphur contaminated soapstock acid oil, oil extracted from spent bleaching earth, oil extracted from palm mill effluent, category 1 animal fats, and tall oil pitch. Some of these materials (e.g. category 1 fats and tall oil pitch) would likely otherwise be used for boiler fuel, and therefore the counterfactual to alternative fuel production would be energy recovery. Some have not normally been extracted in the past, (e.g. oil in palm oil mill effluent) and therefore it would be argued that the systems to extract them have only been developed in order to supply the biofuel industry and the counterfactual would be disposition/decomposition without recovery. Used cooking oil is a particular case because the generation of used cooking oil is widely dispersed (some at large food processing facilities, but much at restaurants and some by households) and therefore the costs involved in aggregating used cooking oil are relatively significant. The development of the biofuel industry has gone hand in hand with the development of supply chains to aggregate and process used cooking oil, but even without biofuel demand some used cooking oil would be used as boiler fuel, and some used cooking oil is added to livestock rations (though not within the EU, where this is prohibited). The counterfactual for the use of EU-generated used cooking oil is therefore probably a combination of reduced collection and some energy recovery, while the counterfactual outside Europe would also include some animal feed use.

6 Conclusions – the role of wastes and/or residues in future fuel production

Reducing waste is generally understood to be a no-brainer from an environmental point of view – it's the sort of thing that would have been obvious to your grandmother 30 years before she'd ever heard of climate change. Disposing of waste is costly and often associated with environmental externalities, so it just makes sense that you would want to minimise waste generation and find ways to use the waste that can't be avoided. This said, while waste minimisation may seem like an obvious environmental and economic goal, we live in a society that has become rather wasteful. Yes, there are costs to disposing of waste, but they tend to be moderate compared to the profits that can be made by doing things in wasteful ways – whether it's adding unnecessary packaging to products for the sake of marketing or convincing people that they need to restock their wardrobe for every fashion season.

Given this alignment between waste reduction looking like an easy policy win and waste generation being very great, the idea that you could make large volumes of something you need out of existing waste is an attractive one. In the case of alternative aviation fuel, the sales pitch is that fuels produced from wastes could make a significant dent in fossil jet fuel consumption, thus helping aviation transition from being an industry that could be seen as being innately energy intensive and environmentally problematic to an industry that has a place in a low carbon future.

While this has considerable appeal on face value, there are some important caveats on the extent to which mobilising wastes into aviation fuel can really deliver benefits. The first caveat is that often materials that an alternative fuel producer might like to characterise as wastes for their marketing are not truly wasted – for example many by-products from industrial processes have perfectly sensible existing uses. The importance of correctly categorising such by-products has long been recognised in alternative fuel legislation, and both the UK and EU distinguish between 'products', and 'wastes and residues', and are selective about which wastes and residues should get extra support under alternative fuel policy.

Even once we eliminate from our feedstock list nominal 'wastes' that actually have good uses, there are still questions to be answered about what the net climate benefit is of using carbon-containing wastes and residues as feedstocks for fuels. There are also regulatory issues that emerge from discontinuities between the way that some of these materials are handled in different aspects of emissions inventories and fuel policies, for example making sure that the physical CO_2 emissions associated with combustion of fossil material in municipal waste do not disappear from inventories when that material is converted into an RCF before combustion.

Perhaps the most obvious question to be asked when using a carbon-based material as a fuel is why there would be a climate advantage to burning something? In some cases such as sustainably available agricultural residues the answer is that the material in question would have decomposed naturally over a short period of time, and thus there is no real additional CO_2 released by burning it (and the release of some fossil carbon is avoided by replacing a fossil fuel). For resources that would be more persistent stores of carbon, such as plastics and larger pieces of timber, the benefit is not so obvious. Regulators in the UK and EU have developed new LCA systems that can take into account the expected displacement emissions from removing materials from an existing use or disposition, but these frameworks are new and relatively untested, and are built on simplifications that could be contested.

In the case of municipal waste containing fossil carbon, such as plastic and used tyres, it seems to be *en vogue* for policy makers to argue that because we do not want to send the materials to landfill we should treat them as free carbon if we use them for energy recovery. This reasoning is contentious. Climate change and landfill reduction are different policy objectives, and there's no reason to believe that conflating them will lead to the best policy outcomes. One can imagine a case in which society ends up pretending that aviation has no climate impact because we haven't thought of a better way to eliminate plastic from landfill – this would seem perverse. This said, if society is unwilling to treat plastic in landfill as a form of permanent carbon storage and is committed to a) eliminating landfills, and b) continuing to generate some plastic waste, then aviation fuel production is probably not the worst thing you could think to do with that material. Establishing an appropriate policy and LCA framework for considering these issues that neither inflates the climate benefit without justification nor precludes the development of a useful technology requires careful thought. It is not good policy to ignore the real net GHG impact of an action just because you think that, on balance, that action is worth taking regardless of the real net GHG impact.

In the particular case of aviation, it is doubly important that we should not overstate the GHG benefits of using alternative fuels because it will distort the wider public discourse about the role of aviation as a high energy intensity industry in a decarbonising society. The aviation industry wants to present a case that its ongoing growth is not in conflict with societal decarbonisation. Others argue that it is not realistic to deliver a carbon neutral aviation industry of the size foreseen by industry forecasts and that some form of growth management would be appropriate. Claims of carbon neutrality based on offsets are already controversial[31] – claims of carbon neutrality based on incomplete LCA of waste-based fuels should also be challenged. In the UK, these issues are at least on the table, and the UK Government has a record of being ahead of the curve in giving serious consideration to issues of identifying appropriate counterfactuals before offering support to new fuel pathways under the RTFO. These will be important considerations as the treatment of RCFs under the RTFO and the proposed UK alternative aviation fuel mandate are finalised.

One revision to the broader policy environment that might give some comfort in these matters would be to try to make sure that the CO_2 releases associated with the use of waste-based fuels are at least identified and included in *someone's* emission inventory. At present, the CO_2 emitted by incineration of fossil waste for energy recovery is recorded in the energy sector in the national GHG inventory, and should be accounted in Scope 2 emissions by the companies that consume that energy. If transport fuel policy uses a displacement analysis approach that leads to a more favourable GHG accounting outcome for waste-based fuels (whereby the consumers of waste-based fuels are permitted to treat them as low or zero emissions in their company reporting) then it would seem appropriate to move those CO_2 emissions into the Scope 3 inventories of the companies that generate the waste in the first place. This would prevent the CO_2 from such fuels from disappearing from the inventory system altogether, and realign the reporting so as to provide a disincentive for waste generation.

[31] E.g. https://www.theguardian.com/environment/2023/may/30/delta-air-lines-lawsuit-carbon-neutrality-aoe

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