Low Carbon Fossil Fuels Sustainability Risks and Accounting Methodology

Final Report

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E4tech (UK) Ltd for the Department for Transport

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Contents

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Acronyms

CCS	Carbon Capture and Storage
CEN	European Committee for Standardisation
CNG	Compressed Natural Gas
DfT	Department for Transport (United Kingdom)
DCL	Direct Coal Liquefaction
EfW	Energy from Waste
FT	Fischer Tropsch
GHG	Greenhouse Gas
L	Litres
LCA	Life Cycle Assessment
LCFF	Low Carbon Fossil Fuel
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MBT	Mechanical Biological Treatment
MHT	Mechanical Heat Treatment
MRF	Materials Recycling Facility
RDF	Refuse Derived Fuel
RFNBO	Renewable Fuel of Non-Biological Origin
RTFC	Renewable Transport Fuel Certificate
RTFO	Renewable Transport Fuel Obligation
SLF	Secondary Liquid Fuel
SNG	Synthetic Natural Gas
SRF	Solid Recovered Fuel
t	Tonnes
TRL	Technology Readiness Level
WFD	Waste Framework Directive

Executive Summary

Decarbonising the transport sector is central to addressing climate change, and alongside other options such as biofuels and electrification, low carbon fossil fuels could contribute to this objective. However there is little consideration to-date of the potential sustainability impacts of these fuels, nor an agreed methodology to assess lifecycle carbon emissions. This study aims to identify and assess these sustainability impacts, propose a methodological framework which could be used for their assessment in relation to specific fuel chains, and assess broad categories of alternative fossil fuels against this framework, recognising that the assessment is highly specific to the specific feedstock used, fuel production process, and final fuel. Not all of the alternative fossil fuels referred to in this report will classify as low carbon fossil fuels, i.e. will have lower carbon emissions than ordinary petrol or diesel.

Alternative fossil fuels can be produced from waste or non-waste fossil feedstocks, or from non-renewable energy. Across this broad scope, the technology routes cover a wide range of Technology Readiness Levels (TRL). Some, particularly those produced from non-waste feedstocks, are already commercial.

The main sustainability risk of alternative fossil fuels is making low or even negative greenhouse gas savings compared to conventional fossil fuels.

A key conclusion of the report is that to understand the real world emissions of alternative fossil fuels, the lifecycle assessment needs to account for where the carbon would otherwise have been destined, had it not been used to make a new fuel product. Adopting this approach, this research illustrates that lifecycle carbon impacts of alternative fossil fuels range from significantly higher, to significantly lower emissions than ordinary petrol and diesel. Very broadly, fuels using carbon sources which would have been sequestered (e.g. in landfill) tend to create a fuel with higher greenhouse gas emissions than those using carbon which would otherwise have been combusted. For example fuels produced from the fossil portion of MSW that would have been landfilled could have GHG emissions which are similar to fossil petrol or diesel. Fuels produced from waste industrial gases, which would always have alternatively been combusted, are highly likely to reduce GHG emissions compared to fossil petrol or diesel.

The report also identifies a range of broader sustainability risks relating to air quality impacts, encouraging the production of more wastes, and of making an inefficient use of resources, for example, through contravening the waste hierarchy. If low carbon fossil fuels are given policy support, the report concludes that robust sustainability criteria should be in place to mitigate these risks. Furthermore, there is a risk that support for non-waste low carbon fossil fuels could support continued fossil fuel use, so should be carefully considered in the context of wider government decarbonisation policy.

Finally, given that the GHG methodology proposed here includes indirect emissions, whilst policies supporting biofuels generally do not, it may not be appropriate to impose the same GHG thresholds on both categories of fuels.

1 Objectives and structure of the report

A number of new technology developers have emerged in recent years aiming to produce fuels from fossil or waste fossil sources, and even some established fossil fuel routes may produce fuels with lower greenhouse gas (GHG) emissions than conventional gasoline or diesel. There is an opportunity for these fuels to contribute to decarbonisation of the UK transport sector, but they could also pose new or additional sustainability risks. Therefore this study aims to:

- Identify and analyse the sustainability risks posed by specific low carbon fossil fuel routes in order to assess whether they should receive government support
- Provide a framework for DfT to assess the sustainability risks associated with any low carbon fossil fuel
- Develop a GHG emissions accounting methodology for low carbon fossil fuels and a set of illustrative GHG emission values for some key fuel chains
- Propose an approach to setting a GHG threshold for sustainable low-carbon fossil fuels

This report is divided into two main sections. The first section (chapter two) provides an overview of the landscape of fuels which could, with sufficiently low GHG emissions, be low-carbon fossil fuels, including technology and commercial readiness and costs where these are available. The objective of this section is to ensure that all relevant sustainability risks are identified, and to provide an overview of which fuel routes and companies are closest to commercial production. The second section of the report (chapter three) defines five key sustainability risks, and proposes a framework to assess fuels against these risks and determine which are likely to be sustainable low carbon fossil fuels. For each risk, its severity and likelihood of occurrence for specific feedstocks or fuels is analysed and practical guidance for assessing this risk in novel fuel chains is provided. Finally key considerations for inclusion of these fuels within the UK and Ireland carbon calculator are discussed in chapter four. Information relating to specific feedstocks and illustrative GHG calculations for fuels produced from a number of these feedstocks is provided in the Appendices.

1.1 Definition of “low carbon fossil fuels” (LCFFs)

In this report, the term Low Carbon Fossil Fuels (LCFFs) is used to denote fuels that ***have the potential*** (e.g. when CCS is used in feedstock processing) to have lower GHG emissions than the typical GHG emissions associated with the weighted life cycle GHG intensity of diesel and gasoline from a variety of feedstocks of 94.1gCO2eq/MJ. It is possible that some of the fuels presented in chapter 2 do not actually result in lower GHG emissions, which will become evident during their GHG assessment. Ultimately, those fuels should be termed “alternative fossil fuels” rather than “low carbon fossil fuels”.

2 Technology landscape of low carbon fossil fuels

This section aims to provide an overview of technology routes that are currently commercialised, emerging into the market, or known to be being pursued by researchers or developers that could be used to produce LCFFs. An overview of these technology routes is given in Figure 1, and additional detail is given in the rest of this chapter. Numerous routes are shown here to be technically possible, for example a wide range of feedstocks can be transformed into syngas, and a wide range of products can be produced from this syngas. However some downstream processes are more likely with certain feedstocks, for technical reasons such as levels of syngas contamination, or for economic reasons. Therefore in the detailed discussion in this section, priority has been given to fuel routes which are being pursued commercially or actively researched today.

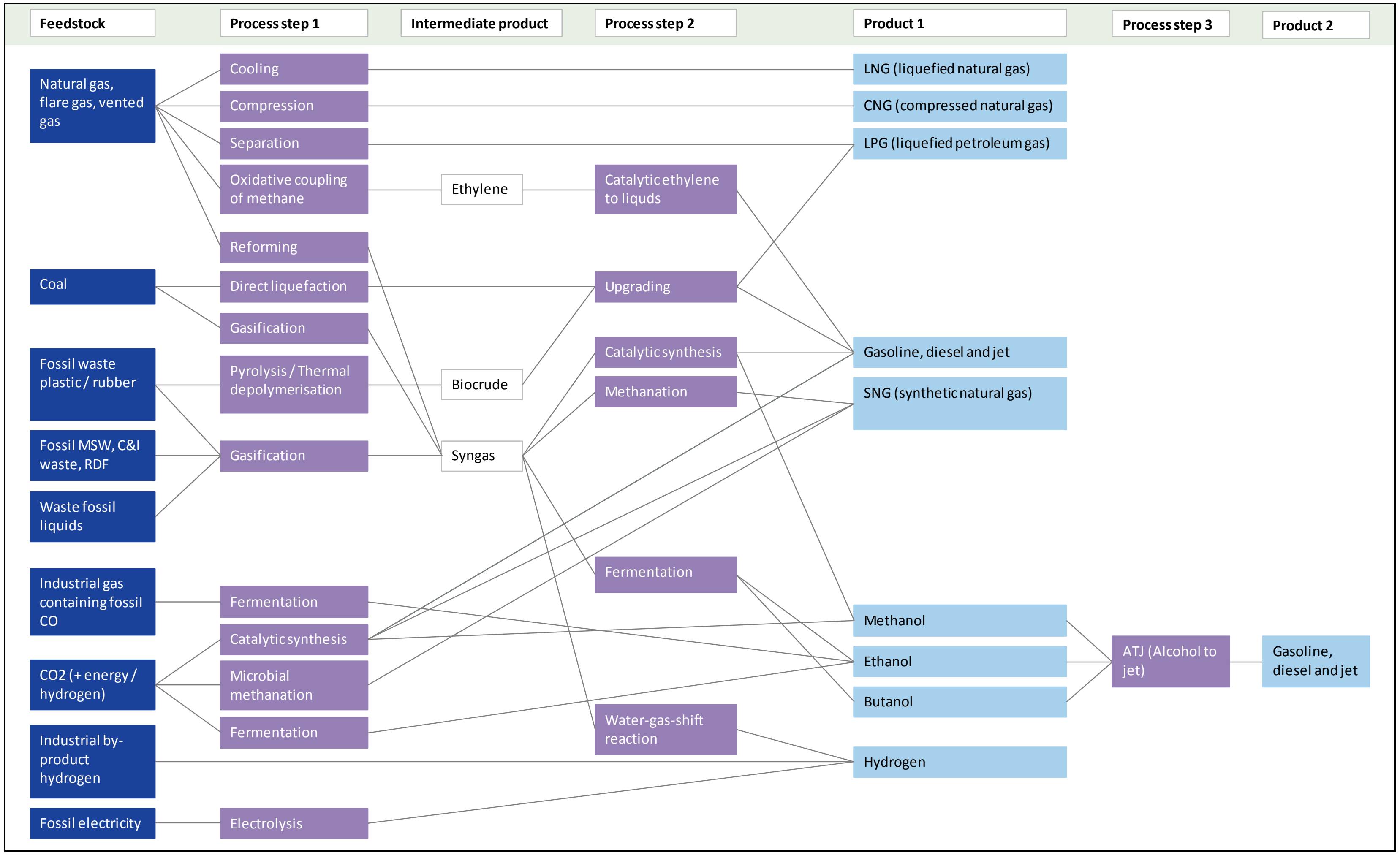

Figure 1 Potential low carbon fossil fuel production routes

The following sections each describe how a particular feedstock can be processed into a particular fuel, providing an assessment of the TRL[1] of each route and case studies of key companies, focussing where possible on companies within the UK.

Processing a particular feedstock into specific fuels(s) requires a system that is highly optimised to the feedstock, the detail of which is out of scope of this report. Nevertheless in many cases a given conversion technology can process a variety of feedstocks, for example the Fischer-Tropsch process can produce gasoline, diesel or jet fuel from syngas, regardless of the origin of the syngas, if sufficient syngas cleaning steps are in place. Therefore for the purposes of this report the high level conversion process is described only once and then referred to later on when required.

2.1 Fuels produced from natural gas

Natural gas is widely processed for use in transport.

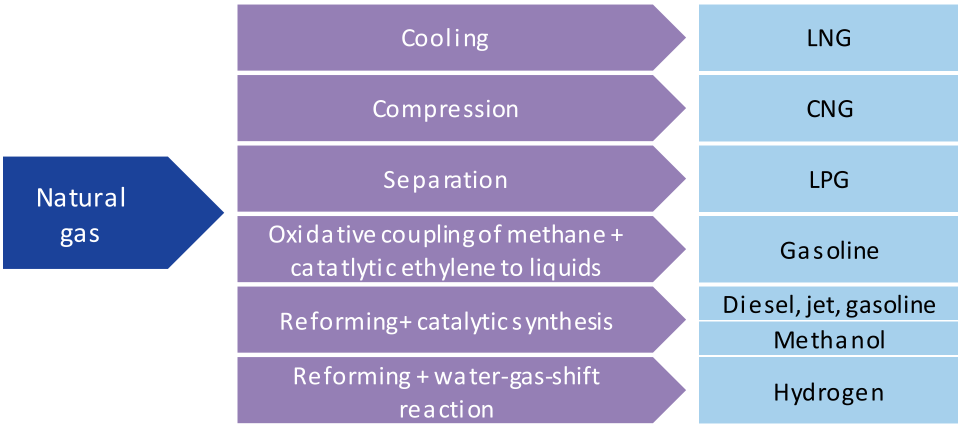

Figure 2: Processing of natural gas into transport fuels

2.1.1 Liquefied Natural Gas (LNG) by cooling

Natural gas is cleaned and purified and then cooled until it reaches its liquid phase in large scale commercial processes (TRL 9), which are operating globally today. The main purpose of this practice is to enable shipping via tanker over long distances, but LNG can also be used as a transport fuel in vehicles, either in dual-fuel engines or dedicated gas engines. LNG vehicles can generally travel further than CNG vehicles before needing to refuel, therefore LNG is often favoured for larger HGVs and for use in ships.[2]

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[1] Technology Readiness Levels are used to assess the maturity of a particular technology, on a scale from TRL 1 to TRL 9. Explanation of the TRL levels used in this study is given in Appendix A.

[2] Le Fevre, C. (2014) The prospects for natural gas as a transport fuel in Europe, Available from: http://bit.ly/2x1bGI1 (Accessed 17th October 2017)

2.1.2 Compressed Natural Gas (CNG) by compression

The compression of natural gas is practiced globally at TRL 9, and CNG can be used either in dual-fuel or dedicated gas engines. As CNG vehicles generally have a smaller range than LNG vehicles, priority markets tend to be smaller road vehicles and 'back to depot' type operations.

2.1.3 Liquefied Petroleum Gas (LPG) by separation

Natural gas liquids, also known as condensates, are produced alongside methane when natural gas is extracted. Natural gas liquids make up between 1% and 10% of the unprocessed natural gas stream. Propane, butane and isobutane are separated from this stream and sold as LPG (TRL 9). Currently LPG is used in around 150,000 UK vehicles, all of which can run on both LPG and conventional gasoline.[3] There is a small cost associated with conversion of the engine to run on LPG, generally between £1000 and £2000. As well as road transport vehicles, around a third of all fork lift trucks in the UK also run on LPG. LPG is subject to lower fuel duties in the UK than conventional gasoline or diesel, and is therefore cheaper at the pump, although this cost saving is partially offset by the additional fuel volume that is required for an equivalent mileage. Nevertheless LPG remains a cheaper fuel option than gasoline or diesel at present.[4]

2.1.4 Gasoline by oxidative coupling of methane and catalytic conversion of ethylene to liquids

In oxidative coupling of methane (OCM), methane reacts with oxygen over a catalyst in an exothermic reaction to form ethylene, water and heat. The ethylene is an intermediate product that has many uses in the chemicals industry, but it can also be oligomerised using another catalytic process to produce liquids such as gasoline.

Case study companies:

- Siluria (USA)
    - TRL 6-7 Silura's OCM catalyst also allows for co-feeding of ethane alongside methane to produce ethylene. Siluria has developed a catalytic process for the conversion of ethylene to gasoline.
    - Siluria has a demonstration plant in Texas, which began operation in 2015. It is operated by Braskem and can produce approximately 350 t/year of ethylene.

2.1.5 Diesel, jet and gasoline by catalytic synthesis of syngas

The gas-to-liquid process involves conversion of natural gas to syngas by sulfur removal followed by partial oxidation, steam reforming or autothermal reforming. This is then followed by Fischer-Tropsch synthesis, which is a catalytic process that can be tailored to produce fuel products such as diesel, jet fuel, naphtha and other products such as waxes from syngas. Large

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[3] Atlantic consulting (2015) Available from: LPG, biopropane and low-carbon transport http://www.lowcvp.org.uk/assets/workingdocuments/LPGBioPropaneDfT.pdf (Accessed on 17th October 2017)

[4] UK LPG (2017) LPG as a transport fuel, Available from: http://www.uklpg.org/about-uklpg/lpg-as-a-transport-fuel/ (Accessed on 17th October 2017)

GtL plants with capacities of 430,000 – over 22,250,000 L/day are located in Malaysia (Shell), Qatar (Shell, Sasol/Chevron), South Africa (Sasol) and Nigeria (Chevron/Sasol).

Case study companies:

- Velocys
    - TRL 7. Focusing on smaller scale plant which allows for targeting stranded natural gas and/or landfill gas. It is the possibility of designing smaller units that might make processing stranded natural gas economically viable that is particularly relevant in the context of this report.
    - Demonstration plant in Oklahoma, USA, is operating, processing landfill and natural gas into FT diesel, naphtha and waxes.

2.1.6 Methanol by catalytic synthesis of syngas

Methanol is an important primary chemical product, which can also be used directly as a fuel (blended with gasoline) or it can be converted to dimethyl ether (DME) for combustion in diesel engines or to gasoline via the ExxonMobil methanol-to-gasoline (MTG) process, or to methyl-tert-butyl-ether (MTBE) for combustion in gasoline engines.

It is produced by converting the natural gas to a syngas by sulfur removal followed by partial oxidation, steam reforming or autothermal reforming. Catalysts are then used to promote the methanol synthesis reactions. Methanol production from natural gas-derived syngas is a commercial technology (TRL 9) with plants globally yielding 2,000 – 5,000 t/d.

More hydrogen is produced in the syngas than is used in the production of methanol. It is possible to increase the yield of methanol by injecting additional CO_2 into the vessel to react with this ‘excess’ hydrogen. This is practiced by some methanol producers.

2.1.7 Hydrogen by water-gas-shift conversion of syngas

Natural gas can be converted to syngas by partial oxidation, steam methane reforming or autothermal reforming. This syngas can subsequently be converted into hydrogen via the water-gas-shift reaction. This is a very common process which is used today to produce 95% of the hydrogen used in the USA and is therefore at TRL 9.[5] This is how the hydrogen used in HVO production is usually produced.

2.2 Fuels produced from coal (with CCS)

Coal can be processed directly into liquid fuels or it can be gasified into syngas and then further processed. Coal-based liquid fuels can only achieve lower GHG emissions than the FQD diesel and gasoline default values if the process is coupled with CCS.

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[5] US Office for Energy Efficiency and Renewable Energy (n.d.) Hydrogen production: natural gas reforming, Available from: https://energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming (Accessed 16th October 2017)

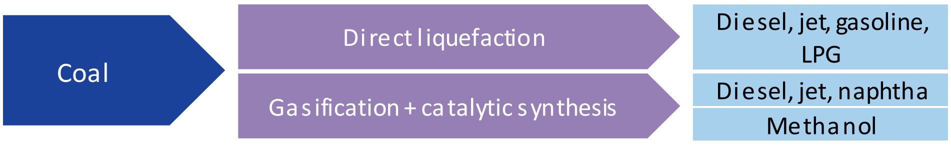

Figure 3: Processing of coal into transport fuels

2.2.1 Diesel, jet and gasoline by direct liquefaction

In direct coal liquefaction (DCL) coal is dissolved in a solvent at high temperature and pressure, followed by the addition of hydrogen over a catalyst (hydrocracking)[6]. This technology is at TRL 8 as the Shenua Direct Coal Liquefaction project is the only commercial project worldwide.[7]

Case study companies:

- Shenhua DCL project (China)
    - An industrial demonstration plant has been in operation since 2008, and produced 400,000 tonnes of synthetic fuels (diesel, jet, naphtha) in 2013. This plant does not appear to have CCS operating.
    - Capacity of the single production line in the Shenhua DCL process is 6,000 t/day of dry coal.

2.2.2 Diesel, jet, gasoline, hydrogen, methanol or SNG by coal gasification + catalytic synthesis

Indirect coal liquefaction is at TRL 9. It involves initial gasification of the coal to produce syngas, which can then be further processed as described in sections 2.1.5, 2.1.6 and 2.1.7 into diesel, jet gasoline, hydrogen or methanol. In addition, catalytic methanation can be used to produce SNG.

Case study companies:

- Sasol (South Africa)
    - Commercial plants (TRL 9) carrying out indirect coal liquefaction to produce FT products in South Africa[8].
- Dakota Gas (USA)
    - At the Great Plains synfuels plant in Dakota, coal is gasified to produce syngas, which then undergoes methanation to produce synthetic natural gas (SNG).
    - 16,000 t/day lignite coal is gasified to produce 3,050 t/day of SNG

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[6] World Coal Institute (2009) Coal: Liquid Fuels, available from: https://www.worldcoal.org/sites/default/files/resources_files/coal_liquid_fuels_report%2803_06_2009%29.pdf, accessed on 14th September 2017

[7] Kong, Z., Dong, X., Xu, B., Li, R., Yin, Q., Song, C. (2015) EROI Analysis for Direct Coal Liquefaction without and with CCS: The Case of the Shenhua DCL Project in China, *Energies*, 8, 786-807

[8] World Coal Institute (2009) Coal: Liquid Fuels, available from: https://www.worldcoal.org/sites/default/files/resources_files/coal_liquid_fuels_report%2803_06_2009%29.pdf, accessed on 14th September 2017

  - The plant started operation in 1988, and has been upgraded since, notably to capture the CO_2 separated during SNG purification which became operational in 2000. The captured CO_2 is used for enhanced oil recovery.

2.3 Fuels produced from waste plastic / rubber

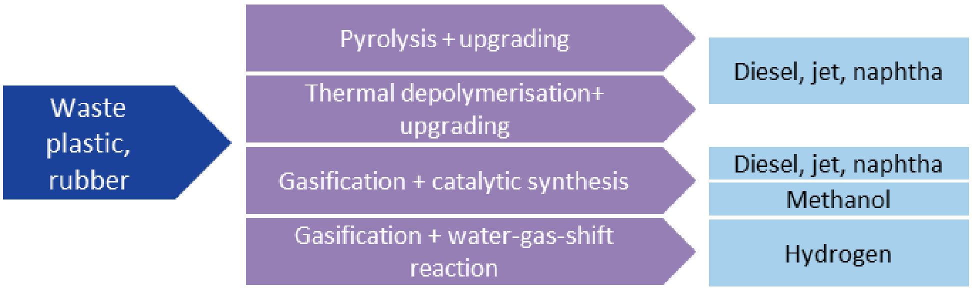

Figure 4: Processing of plastic waste and rubber into transport fuel

2.3.1 Diesel, jet and gasoline by pyrolysis and upgrading

In pyrolysis, materials are thermochemically depolymerised at elevated temperatures and in the absence of oxygen. The resulting pyrolysis oil can then be refined (“upgraded”) into diesel, jet and naphtha and other chemicals.

A report for zero waste Scotland[9] models the economics of various processes for producing liquid fuel from plastics. Their analysis suggests that production of liquid transport fuels by pyrolysis is economically viable with a product price of £564/tonne, even when the gate fee for the plastic is zero. However, a minimum scale of plant would be required for the plant to be viable, which at a £60/tonne gate fee is between 12,000 and 16,000tonnes/annum.

Almost two dozen companies exist globally (including in Europe, the USA and Australia), constructing or operating over 100 facilities, targeting pyrolysis of mixed/non-recyclable plastic wastes to produce either heat and power or liquid fuels. The company case studies therefore focus on those companies active in the UK. TRL for waste plastics to oil for heating and power applications is high (TRL 8-9 in many cases) but upgrading to transport fuels is less developed (TRL 5-7).

Case study companies in the UK:

- Recycling Technologies
  - TRL 6. Pilot plant in operation at Swindon Borough Council UK – processing up to 7,000 t/year into 5,200 t/year of product
  - Process all categories of plastic including non-recyclables into crude-oil like products (trade named Plaxx) of three grades: naphtha equivalent, fuel oils, paraffinic waxes. None of these products are currently marketed as road transport fuels.

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[9] Haig, S., Morrish, L., Morton, R., Onwuamaegbu, U., Peter, S., Wilkinson, S. of Axion Consulting (2013) Plastics to oil products, for Zero Waste Scotland, available from: http://www.zerowastescotland.org.uk/sites/default/files/Plastics%20to%20Oil%20Report.pdf (Accessed on 20th October 2017)

  - In 2016 announced that commercial scale production was reached.[10]
- Cynar
  - TRL 6. Cynar constructed a full-scale plant in Ireland in 2010.
  - Process plastics (grades 4, 5, 6) into pyrolysis oil and then fuels[11][12]
  - Cynar agreed a deal with Suez Sita UK to build 10 facilities, but then left the agreement. Only one plant in Avonmouth was constructed and Cynar went into administration in 2016.[13]
- Integrated Green Energy Solutions (formerly FOY group)
  - TRL 7. In April 2017 signed a US$90 million funding commitment for rollout of 4 commercial sites in the UK with Structured Growth Capital, Inc.
  - Each site is expected to process 200 t/day of plastic into 70M litres per year of product[14]
  - In late 2017 announced plans to invest in a plastics-to-fuel plant in Grimsby producing 69 ML/year of fuel from non-recyclable plastic[15]
- Pyreco
  - TRL 5. In 2011 had plans to build plant in Teesside to produce pyrolysis oil & gas. However no evidence that this started up (2013 struggling with funding for the £80M plant)[16]
- Anergy
  - TRL 9 for electricity applications, likely TRL 6 for transport fuels.
  - Globally active, with over 200 installations in over 50 countries[17], Anergy provides fixed installation of high-temperature pyrolysis: larger plant (in 3 MWe modules) as well as 250 kW-1MWe semi-portable units constructed within shipping containers.

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[10] Lets Recycle (2016) Swindon council to pilot plastics-to-fuel technology, Available from: https://www.letsrecycle.com/news/latest-news/swindon-council-to-pilot-plastics-to-fuel-technology/ (Accessed on 19th October 2017)

[11] Murray, M. (2011)Converting end of life plastic into diesel: the Cynar experience, Available from: https://www.rockwellautomation.com/resources/downloads/rockwellautomation/pdf/events/automation-fair/2011/psug/af11psug_cs08_cynar.pdf (Accessed on 23rd October 2017)

[12] Biofuels digest (2015) 17 Pyromaniax changing the energy landscape, available from: http://www.biofuelsdigest.com/bdigest/2015/10/08/17-pyromaniax-changing-the-energy-landscape/ (Accessed on 19th October 2017)

[13] Brewster, S. (2016) The eight steps in turning plastic back into oil, Available from: https://www.mrw.co.uk/knowledge-centre/the-eight-steps-in-turning-plastic-back-into-oil/10012840.article (Accessed on 19th October 2017)

[14] FOY GROUP LTD (2017) FOY signs funding commitment for the construction of 4 sites in the UK, Available from: http://bit.ly/2il9dpp (Accessed on 19th October 2017)

[15] Biofuels digest (2017) IGE Solutions to invest $26.3 million in UK plastics-to-fuel plant, Available from: http://www.biofuelsdigest.com/bdigest/2017/11/15/ige-solutions-to-invest-26-3-million-in-uk-plastics-to-fuel-plant/ (Accessed on 26th January 2018)

[16] Waste management world (2013) 80m Tyre recycling pyrolysis project struggling to finance teesside plant, Available from: https://waste-management-world.com/a/80m-tyre-recycling-pyrolysis-project-struggling-to-finance-teesside-plant (Accessed on 23 October2017)

[17] Anergy Ltd (n.d.) About us, Available from: http://www.greenanergy.com/about-us.php (Accessed on 19th October 2017)

  - The main products of this pyrolysis process are pyrolysis gas which is upgraded and cleaned to syngas for electricity generation.
  - Anergy are developing technology for production of fuels from waste tyres and waste oil.
- Plastic Energy[18]
  - TRL 7. Headquartered in the UK, with 2 plants in Spain producing pyrolysis oil that is upgraded to inputs for chemicals industry and transport fuels. Feedstock is mixed plastics, mostly contaminated post-consumer plastic waste.
- Tourian
  - TRL 5. Targeting diesel/gasoline production from plastics foils and films in Tees Valley

2.3.2 Diesel, jet, gasoline by thermal depolymerisation and upgrading

Thermal depolymerisation (sometimes also referred to as hydrothermal upgrading) uses hydrous pyrolysis to decompose long chain polymers into short-chain petroleum hydrocarbons in the form of pyrolysis oil, which can then be refined ("upgraded") into diesel, jet and gasoline and other chemicals.

Case study companies:

- Vadxx (USA)
  - TRL 7. $25M commercial scale demonstrator plant started operation in 2017 at 25% of capacity. Full capacity operation in 2018 expected to be 23,000 t/year of waste processed[19]
  - Process a mix of post-industrial and post-consumer waste plastics into liquid transport fuel and lubricants / waxes.
  - Pilot plant at 1/50th of commercial scale was operated for 4 years, also in Ohio.
- Global Renewables (UK)
  - Had plans to develop a facility in the UK but company is now dissolved.

2.3.3 Diesel, jet, gasoline or methanol by gasification of waste plastics + catalytic conversion

Waste plastic can be gasified to produce syngas, which can then either undergo water-gas-shift to yield hydrogen or can be further transformed into SNG, methanol or Fischer-Tropsch liquids. While waste plastics are gasified within the mixed MSW stream processed by companies such as Enerkem, there do not appear to be many developers pursuing gasification of isolated plastics. This may be because the techno-economics of gasification of this feedstock do not appear to be very favourable[20].

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[18] Plastic Energy (n.d.) Technology, Available from: http://plasticenergy.net/technology.php (Accessed on 1st November 2017)

[19] Polymer Ohio (2016) Vadxx Energy Establishes Waste Plastic to EcoFuel™ Facility in Akron, Available from: https://polymerohio.org/vadxx-energy-establishes-waste-plastic-ecofuel-facility-akron/ (Accessed on 19th October 2017)

[20] Haig, S., Morrish, L., Morton, R., Onwuamaegbu, U., Peter, S., Wilkinson, S. of Axion Consulting (2013) Plastics to oil products, for Zero Waste Scotland, available from:

2.4 Fuels produced from the fossil portion of mixed waste streams

Most processes using municipal solid waste (MSW), commercial and industrial waste (C&I waste) or other mixed waste streams pre-process the waste to remove recyclables and some inert materials to produce a dryer, higher calorific value fuel which does not have oversize particles. Depending on composition of the fuel this may be called refuse derived fuel (RDF) or solid recovered fuel (SRF). Fuel production from mixed waste streams produces a partially renewable fuel, only the non-renewable portion of which is within scope of this report. Nevertheless, producers generally aim to maximise the biogenic components of the feedstock as support in Europe and the USA is primarily focussed on the renewable portion of the fuel.

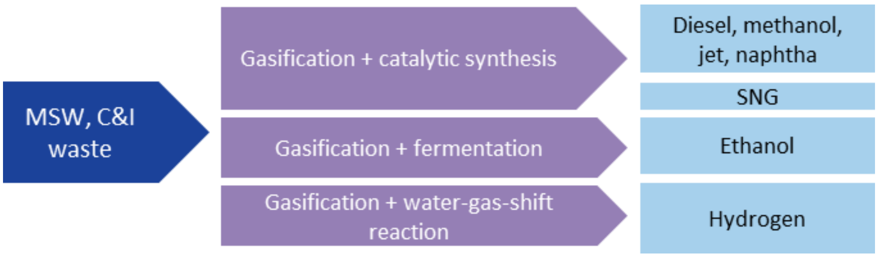

Figure 5: Processing of MSW and C&I waste to transport fuel

Once the feedstock is converted to syngas, theoretically a number of processing options along with a large number of final products are available. The following sections discuss processing routes to final products that are currently known to be actively commercialised.

2.4.1 Diesel/jet by gasification + catalytic synthesis

Refuse derived fuel (RDF) is gasified to yield syngas as intermediate product, which is processed into diesel and jet using variations of the GtL process described in section 2.1.5.

Case study companies:

- Fulcrum Bioenergy (USA)
    - TRL 6-7. Mixed waste stream processing plant (phase 1) is operational in Nevada.
    - Phase 2 of the biorefinery, comprising gasification and FT units, is expected to begin operations in 2020.
    - Target capacity: 175,000 t/year of MSW processed into 40 ML/year of FT liquid
- Velocys / British Airways (UK)
    - TRL 6-7. Project with British Airways, Suez & others to gasify & produce jet fuel by FT synthesis. Stimulated by inclusion of jet within the RTFO development fuel sub-target. Investment decision to be taken in 2019.
    - GreenSky project was originally developed by British Airways with Solena to use an old oil refining site at Thurrock, Essex to process MSW via gasification

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http://www.zerowastescotland.org.uk/sites/default/files/Plastics%20to%20Oil%20Report.pdf (Accessed on 20th October 2017) and FT to jet fuel, but was aborted at the end of 2015 due to financing difficulties, and Solena went into liquidation.[21]

2.4.2 SNG via gasification + catalytic synthesis

In this process RDF is gasified and then tars are removed, followed by several further cleaning and conditioning steps to produce a clean syngas. The syngas can be converted to synthetic natural gas by a catalytic methanation process.

Levelised cost of SNG production in a first-of-a-kind commercial-scale gasification facility processing MSW are estimated to be £50/MWh, with potential to fall to £21/MWh with capex reductions, improved operations, reduced hurdle rate and increased scale that are likely to come from increased deployment of the technology. These costs refer to the combined biological and fossil portion of the SNG.[22]

Case study companies:

- Advanced Plasma Power (UK)
    - TRL 6. The main focus is currently on producing bioSNG from syngas. Syngas is converted to SNG via catalytic water-gas-shift and methanation, followed by CO_2 removal (and addition of some propane) before injection into the gas grid.
    - Pilot plant in Swindon has been running different feedstocks for a number of years. 2.7 MW demonstration plant under construction with DfT and Cadent funding, processing 10,000 t/year of waste. Biogenic SNG is supported under development fuel RTFO sub-target.

2.4.3 Methanol by gasification + catalytic synthesis

In this process, wastes are gasified to produce syngas, which is then cleaned and converted to methanol and/or ethanol via catalytic synthesis. The process used is the same as that outlined in section 2.1.6 for the production of methanol from natural gas-derived syngas, but the process is more challenging due to the high level of impurities in syngas from wastes.

Case study companies:

- Enerkem (Canada/Netherlands)
    - TRL 7-8. Operating first commercial plant in Alberta processing >100,000 t/year of RDF, and a pilot and a demonstration facility in Westbury. Recently added back-end methanol to ethanol conversion step.
    - Developing a project at Cleantech Delta in Rotterdam in partnership with AkzoNobel

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[21] Neslen, A. (2016) BA blames UK government for scrapping of GBP 340m green fuels project. The Guardian. Available from https://www.theguardian.com/environment/2016/jan/06/ba-blames-uk-government-for-scrapping-of-340m-green-fuels-project (Accessed 23rd October 2017)

[22] GoGreenGas (2017) BioSNG Demonstration Plant Summary of Commercial Results, Available from: http://gogreengas.com/wp-content/uploads/2015/11/P167-BioSNG-Commercial.pdf, Accessed on 20th October 2017

2.4.4 Ethanol by gasification + microbial fermentation

Waste gasification produces syngas, which is then cleaned and fermented using microbes developed for this purpose.

Case study companies:

- LanzaTech
  - TRL 5. Pilot plant installed at MSW gasification site

2.4.5 Hydrogen by gasification + water-gas-shift reaction

Waste gasification produces syngas, which can then be processed using the water-gas-shift reaction into hydrogen. The syngas-to-hydrogen step is analogous to that used in the production of hydrogen from methane, which is globally practiced at commercial scale (section 2.1.7). However there is little experience worldwide with waste gasification to hydrogen, which remains at TRL 5.

Case study companies:

- Powerhouse Energy (UK)
  - TRL 6/7 for electricity generation from syngas, TRL 5 for catalytic conversion of syngas to transport fuels
  - Developing a waste-to-hydrogen facility, targeting hydrogen use in the transport sector.[23]

2.5 Fuels produced from gasification of waste fossil liquids

Waste fossil liquids encompass a range of possible feedstocks, including waste lubricant oils, coal slurry, petroleum sludge and waste solvents.

Figure 6: Processing of waste fossil liquids to transport fuel

2.5.1 Methanol by gasification + catalytic synthesis

Waste fossil liquids can be gasified to produce syngas, which is catalytically processed into methanol as outlined in section 2.1.6.

Case study companies:

- SVZ Schwarze Pumpe
  - TRL 8. Sustec Schwarze Pumpe GmbH operated a plant since the 1970's, processing a range of feedstocks, including fossil waste oils. The mixed waste oils were first dehydrated and de-sludged, converted to syngas in two entrained-flow gasifiers, and then converted to highly purified methanol via

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[23] PowerHouse Energy Group (2017) PowerHouse Energy hits major milestone with pre-FEED completion, Available from: https://www.powerhouseenergy.net/powerhouse-energy-hits-major-milestone-pre-feed-completion/ (Accessed on 5th December 2017)

    methanol synthesis and distillation. The plant never became economically viable.
    - The company went into administration in 2010. Many of the peripheral systems necessary for the process have since been dismantled.

2.6 Fuels produced from industrial gas containing fossil CO

Figure 7: Processing of industrial fossil CO gases to transport fuel

2.6.1 Ethanol by microbial fermentation

Industrially occurring gases that are rich in CO can be converted to ethanol (as well as butanol and other non-fuel chemicals) by proprietary microbes developed for this purpose.

Case study companies:

- LanzaTech (China, Belgium, India, South Africa)
    - TRL 7-8. Constructed two facilities in China producing 300 t/year of ethanol, one of which is still operating, and a facility in Taiwan producing around 750 t/year which is now shut down.
    - Two commercial scale projects under construction at steel mills to use blast furnace and basic oxygen furnace gases (Belgium & China).
    - Planning demonstration facilities to use CO-rich gases from hydrogen purification at refinery in India and ferro-alloy production off-gases at facilities in South Africa.

2.6.2 Jet by microbial fermentation + AtJ

Alcohol to jet technology is being developed by a number of companies, including Swedish Biofuels, Gevo, and Lanzatech/the Pacific Northwest National Laboratory (PNNL) in the USA. These routes typically target biomass-derived alcohols in order to produce biojet fuel, but as fossil-derived alcohols are chemically the same, the technologies could equally be applied to non-biogenic alcohols. Alcohol to jet processes are currently at TRL 5-6.

Case study companies:

- Lanzatech
    - Lanzatech has produced over 15,000 L of synthetic paraffinic kerosene jet fuel blendstock from both biogenic and non-biogenic ethanol sources, including ethanol produced by fermentation of steel mill waste gases in their Shougang (China) demonstration facility. The AtJ technology was developed in collaboration with the US PNNL.
    - A demonstration-scale facility is in the design-phase. This will produce 11 ML/year of jet and diesel fuel using ethanol produced from industrial waste gases and lignocellulosic ethanol.

2.7 Fuels produced from CO2

For these fuels to be within scope of this study, the hydrogen used in their production must be fossil hydrogen. However most companies developing these routes are targeting fuels produced from CO_2 and renewable hydrogen, to produce a RFNBO.

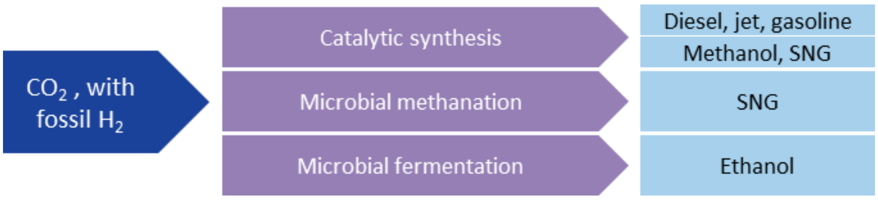

Figure 8: Processing of CO_2 with hydrogen to transport fuel

2.7.1 Methanol by catalytic methanol synthesis

CO_2 can react with hydrogen over a catalyst to produce methanol.

Case study companies:

- Carbon Recycling International
    - TRL 7. Plant in Iceland uses (renewable) grid electricity for electrolysis to convert waste CO_2 from a local geothermal plant into 4000 t/year methanol via catalytic synthesis. Developing 40,000 t/year commercial scale projects in Europe & Asia using grid electricity.
    - H2020 FreSMe project in Sweden aims to demonstrate the production of methanol via catalytic synthesis from CO_2 separated from steel mill off-gases and H_2 from electrolysis. Use of fossil electricity to produce the hydrogen would bring the route within scope of this study.
- Air Fuel Synthesis were pursuing this route but company now dissolved.
- Bse Engineering
    - TRL 6. Planning to build small-scale units that are to be installed near renewable electricity generators to use excess electricity to produce hydrogen in discontinuous electrolysis. Catalytic methanol synthesis using catalysts supplied by BASF[24]
    - Bse Engineering recently competed a demonstration project funded by the German Ministry for Education and Research where different catalysts were tested[25]
- BioMCN
    - BioMCN react CO_2 with excess hydrogen produced in the conventional methane to methanol production process to produce additional methanol.

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[24] BASF and bse engineering (2017) Gemeinsame Presseinformation, Available from: http://www.bse-engineering.eu/news/BASF-bse-small-scale-co2-methanol-plants_GER.pdf, (Accessed on 20th October 2017)

[25] Bio-M (2017) Projekt, Available from: http://www.bio-m.eu/ , (Accessed on 20th October 2017)

2.7.2 Diesel by catalytic synthesis

Reaction of CO_2 with hydrogen over a catalyst can produce hydrocarbons, which can be refined into a diesel fuel.

Case study companies:

- Sunfire:
  - TRL 6. Pilot plant in partnership with Audi in Germany. Producing small quantities of liquid hydrocarbon (which is refined to diesel) via catalytic synthesis of H_2 that is produced by high temperature electrolysis, and CO_2 obtained from a biogas plant. Also known as power to liquids.
- Carbon Engineering:
  - TRL 5-6. Capture CO_2 from the air and react it with hydrogen to generate first syngas and then hydrocarbons, with a focus on diesel and jet fuel. Currently aiming to produce RFNBO fuel by using renewable electricity to produce hydrogen via electrolysis. Use of non-renewable electricity would bring it within scope of this study
  - Claim that when scaled up this process can produce fuels for less than $1/L[26]

2.7.3 SNG by catalytic synthesis

Reaction of CO_2 with hydrogen over a catalyst can produce SNG.

Case study companies:

- Hitachi Zosen Inova Etogas GmbH
  - TRL 6-7. Developed Audi e-gas in collaboration with Audi in Germany, demonstration plant went online 2013, currently delivering 300 m^3/hour SNG to the gas grid.
  - Another SNG pilot plant online at HBFZ research centre in Germany, delivering 4 m^3/hour to the gas grid
  - A few other small research initiatives in Germany.

2.7.4 SNG by biological synthesis (microbial methanation)

Microorganisms can process CO_2 and hydrogen into methane in a process called microbial methanation.

Case study companies:

- Viessman Group and Audi
  - TRL 5-6. Developed SNG production via biological/microbial methanation, first sizeable pilot plant of its kind started injecting 15-55 m^3/hour SNG into the gas grid in Germany in 2015.
  - Smaller research plant went online in 2012 with 5 m^3/hour

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[26] Carbon Engineering (2017) Air to Fuels, Available from: http://carbonengineering.com/about-a2f/ (Accessed on 5th December 2017)

2.8 Hydrogen

Hydrogen can be produced from a range of sources: biomass, fossil fuels, fossil wastes and directly from electricity. Hydrogen produced from fossil electricity, and hydrogen produced from fossil fuels such as natural gas are both within scope of this report.

2.8.1 Hydrogen from fossil electricity

Hydrogen production from electricity via electrolysis is at TRL 9. However, given the high cost of hydrogen production from electrolysis and the poor GHG performance of transforming fossil based electricity into hydrogen, strong (policy) drivers targeting air quality may be needed for producers to target this in particular. If hydrogen is produced from grid electricity then a portion of that hydrogen is likely to be produced from fossil electricity.

2.8.2 Hydrogen as a by-product of industrial processes

In some industrial processes hydrogen can be produced in excess as a by-product of the process. Hydrogen production by this method is at TRL 9. One notable example of this is in the chlor-alkali process. In the majority of plants the hydrogen is captured and used as a chemical feedstock or for provision of heat and/or power to the plant[27], but it has been estimated that 216,000 t/year (equivalent to 15% of the global chlor-alkali hydrogen production) is vented.[28]

3 Sustainability assessment framework

3.1 Summary of sustainability risks and sustainability assessment framework

For the low carbon fuel chains described in the technology landscape (section 2) to be supported through policy, it needs to be ascertained whether they pose any sustainability risks. This section identifies key sustainability risks and proposes a framework for assessing whether fuels pose a risk.

The key sustainability risks are:

1. Production and use of the fuel causes non-GHG environmental impacts, including **air pollution** and other **local environmental impacts**
2. Use of a waste feedstock will **increase production of that waste** (if the feedstock is a waste)
3. Other viable options for using the feedstock are **higher up in the waste hierarchy** (if the feedstock is a waste)
4. Production and use of the fuel will lead to **increased lifecycle GHG emissions**

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[27] Euro Chlor (2010) The European Chlor-Alkali industry: an electricity intensive sector exposed to carbon leakage, Available from: http://www.eurochlor.org/media/9385/3-2-the_european_chlor-alkali_industry_-_an_electricity_intensive_sector_exposed_to_carbon_leakage.pdf (Accessed on 16th October 2017)

[28] Cox, R. (2011) for Fuel Cell and Hydrogen Energy Association, Waste / Byproduct hydrogen, available from: *https://energy.gov/sites/prod/files/2014/03/f12/waste_cox.pdf (Accessed on 16th October 2017)*

5. Production of these fuels will support **increased production and use of fossil fuels**

Figure 9 proposes a framework that can be used by DfT to evaluate the sustainability of a low carbon fossil fuel. A series of questions (shaded in dark blue and numbered 1 – 5) aim to assess whether a fuel poses any of the five sustainability risks identified above. The final question is not solely a sustainability question: the GHG saving threshold adopted for each fuel type is likely to be influenced by DfT policy priorities and the GHG methodology used for that fuel type.

Whether a fuel is considered sustainable is usually specific to a given production process, and even in some cases to a given consignment of feedstock. Therefore while a summary of the risk across different fuel chains is given for each sustainability risk (section 3.3 to 3.8), for each question a recommendation is given as to the level of detail that would be required for the assessment of the sustainability of a particular fuel were LCFFs to be supported by DfT.

The questions in Figure 9 that are shaded purple classify the fuels in order to target appropriate sustainability assessment questions, and to define the appropriate GHG calculation methodology to use.

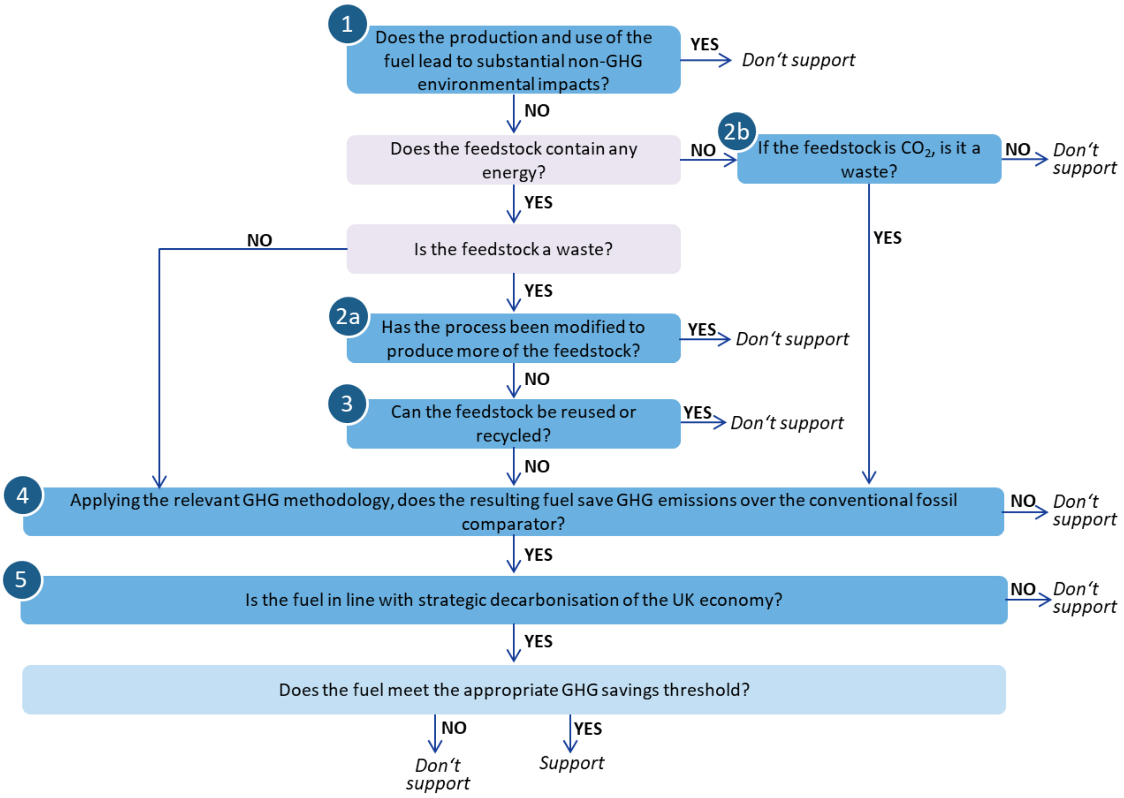

Figure 9: Sustainability assessment and support decision tree for low carbon fossil fuels

In the following sections 3.3 to 3.8 each of the key sustainability risks is examined in turn. Each risk is explained, and identified as most relevant to the **feedstock,** the fuel **production process,** or the **final fuel**. The severity and likelihood of this risk materialising for the relevant part of each fuel chain is summarised in a table (criteria on which these are assessed are given in Appendix B), and additional explanation relating to specific feedstocks or fuels is given in the

Appendices. Finally for each risk we explore in more detail how DfT can assess the relevant question 1 to 5 of the sustainability framework above in order to support truly sustainable fuels.

3.2 Defining LCFFs

The purple boxes in the sustainability assessment framework split fuels into three different categories: those for which the feedstock contains no energy, those which are made from waste feedstocks, and those which are made from non-waste feedstocks.

Feedstock is here defined as an input to the fuel production process which provides atoms to the final fuel. For example: natural gas which is reformed into methanol is a feedstock, plastic which is pyrolysed to make diesel is a feedstock, and water which is split by electrolysis to make hydrogen is a feedstock. Natural gas which is combusted to provide process heat and water used for cooling are not feedstocks.

3.2.1 Does the feedstock contain any energy?

This should be assessed on the basis of the lower heating value (LHV) of the dry feedstock, and is the same criteria as currently proposed for differentiating between RFNBOs, for which the answer to this question would be ‘no’, and biofuels, for which the answer would be ‘yes’. Both CO_2 and water contain no energy, so when the atoms in a fuel come only from these sources, question 2b is answered ‘no’. For consistency with existing RTFO policy, the treatment of these fuels should parallel RFNBO policy. For example the existing methodology for determining the renewable fraction of a partial RFNBO, which states that the renewability of the products is determined based on the percentage of all the energy inputs to the process that are renewable[29], should also be applied to determining the fossil portion of a partial RFNBO.

If any of the energy content of the fuel comes from the atoms of the feedstock then the answer to this question must be ‘yes’. For example if a microorganism processes both CO and CO_2 from an industrial waste gas stream then the answer to the above question is ‘yes’. This currently follows the same principle as the definition between RFNBOs and biofuels, but should that change then this LCFF classification method should also be reviewed.

3.2.2 Is the feedstock a waste?

The Waste Framework Directive (WFD)[30] identifies a feedstock as a waste if the holder ‘discards or intends to discard’ the material, and this criteria should be applied in the assessment of this question. . The UK guidance clarifies that discarding covers activities and operations such as recycling and recovery options, as well as disposal or incineration, so that even material that is intended to be recycled is by this definition a waste. The following feedstocks are likely to be considered as wastes, though each feedstock should be assessed individually:

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[29] Excluding biomass-derived energy, see the Draft RTFO Year 11 Process Guidance, Part 1.

[30] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance), available from: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098

- Industrial off-gases
- Waste fossil plastic / rubber
- Mixed municipal and commercial and industrial waste
- Associated natural gas that is otherwise flared or vented
- Waste fossil liquid

Note that the aim of this question is not to assess whether use of this waste is sustainable, but simply to determine whether further criteria concerning waste sustainability should be applied to this feedstock.

DfT already operates a process for assessing whether biomass feedstocks are wastes, which was reviewed by DfT and E4tech in December 2016. A similar process could also be used for assessing fossil feedstocks.

3.3 Production and use of the fuel will cause non-GHG environmental impacts

3.3.1 Risk description

3.3.1.1 Air pollution

This sustainability risk applies to the final **fuel**. Air pollution from especially older diesel and gasoline engines currently cause significant environmental and human health impacts across the UK. The likelihood of a given fuel increasing local air pollutants depends primarily on:

1. **Emissions regulation** - What emissions regulation is in place for the sector concerned?
2. **Fuel standards** - Does the end fuel (either pure or blended) comply with a European Committee for Standardisation (CEN) standard or is at least classed as a reference fuel for compliance testing?
3. **Vehicle technology** - Will the fuel be used in new vehicles or into existing fleets with no or some (retrofit) modification?

If this risk was to occur the impact is judged to be **severe**.

Emission regulation:

Emission limits on new land based vehicles and machinery have become increasingly stringent over the last 20 years, which has led to automotive manufacturers bringing increasingly complex after-treatment technologies to market in order to meet these limits. Some fuel standards have had to be updated (for example lead and sulfur reduction) in order to meet these regulations.

However, emissions regulations in shipping and especially aerospace are less stringent than for land-based vehicles. Bringing a new fuel to market in sectors with less emission regulation can pose a risk of increased levels of pollutant emissions, but could also represent an opportunity to reduce emissions compared to current levels.

Fuel standards

The CEN standards and reference fuel standards are the two main fuel standards for road transport fuels that apply in the EU.. CEN standards apply to most commercially available fuels and are set by national standards organisations in conjunction with stakeholders in the supply and demand sectors. The reference fuel standard is typically developed ahead of the full CEN standard, and is mostly used for new vehicle compliance testing. Fuel standards in this report refer to the end-fuel, not the individual component – for example ethanol can be blended into gasoline to meet the EN228 gasoline standard even though ethanol for blending has a separate standard.

Standards aim to ensure that both the fuel infrastructure and the vehicles operate safely and as intended, including the functioning of the engine and the exhaust after-treatment systems. Within Europe, manufacturers must ensure that all new vehicles meet regulated pollutant limits using the reference standard fuels. These reference standards are a slightly narrower specification fuel than the fuel for sale at forecourts across the EU which is covered by the CEN standard. Fuels which only have a reference standard but not a CEN standard (e.g. ED95, a fuel containing 95% ethanol and 5% ignition enhancer for use in adapted compression ignition engines) can only be used in a captive fleet and new vehicles designed to run on these fuels, but must still meet legal emissions requirements. New vehicles designed for fuels which do not have a standard cannot be demonstrated to meet the emission limits and can therefore not legally be sold in the EU. Vehicles already in the fleet might be tolerant of a new fuel, but might see different levels of pollutant emissions compared to the existing fuel.

Therefore a new fuel that complies with an existing CEN or reference fuel standard will have a lower risk profile compared to a non-standardised fuel.

Standards exist for aviation fuel, but to-date these have mostly focussed on performance characteristics rather than emissions control.[31] No global standards apply to ocean going shipping fuel, although limits on marine fuel sulfur content will be introduced by the International Maritime Organisation from 2020.

Vehicle technology of fuel end-user

The introduction of stricter emission legislation in recent years has led to the introduction of novel engine and after-treatment technology. Vehicles and machinery tend to remain in operation for a considerable time ranging from between 10 years for passenger vehicles to 40 years for ships and aircraft. Therefore the sector-specific UK fleet consists of a mix of different technologies that are implemented in different ways for each product model.

New fuels supplied into the market can be used in three broad ways in the vehicle fleet:

1. Used in new vehicles
2. Used in vehicles in the existing fleet with no modifications
3. Used in vehicles with retro-fit technology

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[31] Kapadia, Z. Z., Spracklen, D. V., Arnold, S. R., Borman, D. J., Mann, G. W., Pringle, K. J., Monks, S. A., Reddington, C. L., Benduhn, F., Rap, A., Scott, C. E., Butt, E. W., and Yoshioka, M.: Impacts of aviation fuel sulfur content on climate and human health, Atmos. Chem. Phys., 16, 10521-10541, https://doi.org/10.5194/acp-16-10521-2016, 2016

The risk profile follows the list above:

- Bringing a new fuel into the market alongside new vehicles will mean that, as long as the new fuel has a standard, those new vehicles will have to meet legal emissions regulations (when the vehicle is first introduced into the market) with the fuel, therefore the manufacturer has largely eliminated the risk.
- Using a new fuel in the existing fleet has a fairly low risk as long as the fuel meets existing fuel standards. Whilst the existing fleet may have lower emissions standards than new cars, use of a new fuel in that fleet, as long as it meets existing fuel standards, is unlikely to increase emissions compared to the existing fleet running on conventional fuel of the same standard.
- Bringing a new fuel into the market for use in vehicles with retrofit technology has a larger risk as these vehicles and technology do not have to undergo the rigorous compliance testing required for new vehicles. The recently-introduced Clean Vehicle Retrofit Accreditation Scheme[32], which verifies that vehicles with retrofit technologies comply with the emissions levels required for Clean Air Zones, mitigates this risk, but only for vehicles which choose to take part in the scheme.

3.3.1.2 Non-GHG environmental impacts of fuel production

The risk of causing local environmental impacts, such as toxic or hazardous emissions or by-products, and high water consumption in water-stressed areas, is applicable to all **production processes** for potential low-carbon fossil fuels. The extraction of primary fossil fuel **feedstocks** can also cause **severe** local environmental impacts. In general, processes for the production of low-carbon fossil fuels are not anticipated to pose a more severe risk of local pollution than other industrial processes, so this risk category is judged to be **moderately severe** for these fuel routes.

It should be noted that currently DfT does not require biofuels to meet sustainability criteria regarding local environmental pollution in order to obtain Renewable Transport Fuel Certificates (RTFCs).

3.3.2 Summary of risk across different fuel chains

3.3.2.1 Air pollution

Table 1 summarises the likelihood of fuel types increasing local air pollutant emissions compared to conventional gasoline or diesel. The severity if any of these did occur is **severe**. Each individual fuel may fit into one or more of these categories (e.g. ethanol is supplied under CEN standard EN228 and is regularly used in both new and existing fleet vehicles), and may fit into different categories depending on the blend in which it is supplied to the market. For each fuel type the standards in place and vehicle technologies in which they are commonly deployed are discussed in Appendix C.

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[32] Low CVP (2018) Clean Vehicle Retrofit Accreditation Scheme, Available from: http://www.lowcvp.org.uk/projects/joint-working-projects/clean-vehicle-retrofit-accreditation-scheme.htm (Accessed on 22nd January 2018)

Table 1 Summary of likelihood of novel LCFF increasing local pollutant emissions compared to existing fuels, depending on legislation and fuel standards and vehicle technology. Criteria for assessment of likelihood of risk occurring are outlined in Appendix B.

		Vehicle technology					
		New		Existing Fleet		Retrofit	
		Regulated	Non-regulated	Regulated	Non-regulated	Regulated	Non-regulated
Fuel standard / legislation	Emissions legislation in place[33], fuel has a standard	🟩	🟨	🟩	🟨	🟨	🟨
	Emissions legislation in place, no fuel standard	N/A	N/A	🟨	🟨	🟨	🟨
	Limited / no emissions legislation in place	🟨	🟨	🟨	🟨	🟨	🟨

The use of low carbon fossil fuels could also present an opportunity to improve air quality, as some LCFFs could have substantially lower tail-pipe emissions compared with conventional gasoline or diesel. Examples include the use of hydrogen in fuel cell cars, and the use of synthetic aviation fuels blended into kerosene. These are discussed in more detail in Appendix C.

3.3.2.2 Non-GHG environmental impacts of fuel production

All production processes have some likelihood of causing local environmental impacts, but this may be higher if:

- Plant is using hazardous or contaminated waste feedstocks
- Production of fuel takes place outside of the EU where there may be less stringent environmental regulations

Nevertheless local environmental pollution can generally be controlled by good practice and robust waste treatment measures at the plant. It is impossible to generalise for each fuel chain whether these measures may be in place, therefore all processes are assessed (in Table 2) to have some likelihood of causing non-GHG environmental impacts. Assessment of risk severity is described in section 3.3.1.2.

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[33] Sectors for which emissions legislation are in place in the UK are light duty vehicles, heavy duty vehicles and non-road mobile machinery

Table 2 Likelihood and severity of that LCFF production will cause other non-GHG environmental impacts.

	Likelihood of risk occurring	Severity of risk if it occurs
Extraction of primary fossil fuel feedstocks	🟧	🟥
Production process – all routes	🟧	🟧

3.3.3 How this risk is assessed

In the sustainability assessment framework provided in section 3.1, the first question aims to mitigate the risk that production and use of low carbon fossil fuels will cause non-GHG environmental impacts, including air pollution. We propose this risk should be assessed and mitigated by the following process:

- If fuel is supplied into the road transport sector with a CEN / reference standard, this provides sufficient risk mitigation.
- If fuel is supplied into the road transport sector without a standard, DfT should require additional risk assessment into regulated and unregulated pollutants from fuel, when it is used in the anticipated vehicle types.
- If fuel is supplied into the aviation sector, DfT should require evidence from the fuel producer that the fuel will not increase local pollution.
- Currently DfT does not require biofuels to meet criteria on local environmental pollution in order to obtain RTFCs and be compliant with RED sustainability requirements. Given that there is a similar risk of local environmental impacts in LCFF production processes, their treatment should be the same as biofuels, therefore compliance with the relevant environmental laws and permitting requirements for the production plant is considered sufficient to meet this sustainability criteria.
- Whilst there is a high risk of local environmental impacts associated with primary fossil fuel extraction, this equally applies to conventional gasoline and diesel, so it would be more appropriate to tackle this sustainability risk through wider government policy.

3.4 Risk that use of a waste feedstock will increase production of that waste

3.4.1 Risk description

Using waste material as a **feedstock** for liquid transport fuel production may increase the value of that waste and therefore incentivise increased production or reduce the driver for industry to improve resource efficiency in production. This undesirable effect implies inefficient use of resources and therefore contravenes the waste hierarchy which lists waste prevention as the highest priority for waste management.

This risk is considered **severe** if it occurs, given existing UK legislation implementing the waste hierarchy.

3.4.2 Summary of risk across different fuel chains

Table 3 Summary of risk profile for specific fuel production routes. Criteria for assessment of severity and likelihood of risk occurring are outlined in Appendix B.

	Likelihood of risk occurring	Severity of risk if it does occur
Industrial wastes	🟧	🟥
Post-consumer wastes	🟩	🟥

Most **industrial wastes** (solid, liquid and gaseous) are produced in response to demand for the main product, and generally processes are optimised so as to minimise their generation. However it is possible that strong government support could valorise the waste sufficiently to incentivise changes to the process, to increase waste production.

For **MSW and post-consumer waste plastics**, the consumer is unlikely to see any financial gain if the discarded waste has a higher value because of its use in transport fuel production. It is therefore unlikely that valorising this waste will cause more of it to be produced. There is a small risk that if people know that their waste is going to fuel production rather than landfill or incineration then they may be less incentivised to reduce waste production, but conversely if production of liquid fuels can offer a higher value use for some plastic streams then it may improve the economic case for segregated collections.

3.4.3 How this risk is assessed

This risk is addressed through questions 2a and 2b in the sustainability assessment framework.

3.4.3.1 Questions 2a: has the process been modified to produce more of the feedstock

If the **producer** of the feedstock **does not benefit from the additional value** of this resource then it is highly unlikely that the production of that material will increase with rising value.. DfT could maintain a list of such feedstocks to which this applies, which do not need to provide further proof on this question. Such a list would likely include local-authority collected MSW, post-consumer waste plastic, and waste tyres.

If the **producer** of the feedstock **does benefit from the additional value** of this resource then DfT should require evidence that the process has not been modified to produce more of this feedstock. Evidence might include several years' operational records from the plant producing the feedstock to demonstrate that the process has not been altered to generate additional feedstock. Producers should also provide information on what affects production of the waste, whether there are processes that produce less waste and why they have not been used.

In the case that additional waste /by-product material is produced, the whole feedstock should be disqualified from support, in line with current rules for waste biogenic feedstocks.

Addressing the risk that valorising a feedstock removes incentives to improve process efficiency is challenging as there are likely to be many factors influencing an operator's decision to modify or move to an alternative production process. In the case that the producer of the waste benefits from the additional value, we suggest DfT monitors this risk by requiring information from producers on how the level of generation of waste from their plant compares to typical / average waste generation in the industry. DfT could also require information on what affects production of a given waste, whether there are processes that produce less waste and why they have not been implemented. If it becomes apparent that DfT is supporting feedstocks generated in processes which are particularly wasteful, this should be further reviewed.

Many of these questions are already posed in the existing DfT process for assessing sustainable biomass wastes, or were suggested for inclusion in E4tech's 2016 review of this process, therefore it is likely that the existing process and data collection form would not need substantial modification for assessing fossil wastes.

3.4.3.2 Question 2b: if the feedstock is CO_2, is it a waste?

In line with the legislation around RFNBO fuels that is currently under consultation, DfT should not support fuels produced from CO_2 where that CO_2 has been produced specifically for the purpose of making the fuel. This should be assessed in the same way as it is assessed for RFNBOs.

3.5 Risk of feedstock not meeting the waste hierarchy

3.5.1 Risk description

This sustainability risk applies to all **feedstocks** categorised as a waste (see section 3.2.2). The waste hierarchy is a central concept of the EU Waste Framework Directive (WFD), which requires that waste is managed in line with the following order of priority:

1. Prevention
2. Re-use
3. Recycling
4. Recovery
5. Disposal

The use of waste for energy purposes (including fuels) is classified under the WFD as "recovery" and thus ranks low in the waste hierarchy. Re-purposing of waste through recycling is considered to be a more beneficial use of the waste from a resource/circular economy perspective. Therefore, the application of the waste hierarchy is an important aspect of assessing the sustainability of a particular fuel and its consideration will ensure alignment with other government policy and the EU WFD. Not meeting it is considered a **severe** risk. Although waste gases are not within scope of the WFD, to provide a consistent comparison with other waste fossil feedstocks, waste gases are here considered in the context of the waste hierarchy.

The waste hierarchy is also a guide to balancing the impact of GHG emissions with other sustainability concerns. Guidance from Defra[34] recognises that in terms of GHG emissions, sending plastics to landfill may be preferable to other forms of energy recovery, because plastics degrade extremely slowly. However, because landfill is generally less preferable in terms of the other environmental impacts commonly included in life cycle assessments (LCA), it is kept at the bottom of the hierarchy.

3.5.2 Summary of risk across different fuel chains

A summary of the likelihood of a given feedstock not meeting the waste hierarchy is given in Table 4, based on the most common alternative uses of these feedstocks in the UK. Details of these common alternative uses, which form the basis of this assessment, are found in Appendix D.

Table 4 Summary of risk profile for specific fuel production routes. Criteria for assessment of severity and likelihood of risk occurring are outlined in Appendix D.

Feedstock	Likelihood of feedstock not meeting waste hierarchy	Severity of risk if it does occur
Waste fossil plastics	🟧	🟥
Waste tyres	🟧	🟥
Mixed waste streams	🟧	🟥
Waste fossil liquids	🟩	🟥
Waste industrial CO gases	🟩	🟥
CO_2	🟩	🟥
Hydrogen (industrial by-product)	🟧	🟥

3.5.3 How this risk is assessed

To support compliance with the waste hierarchy, policy has to safeguard against:

1. Diverting material streams that are currently recycled to fuel production instead,
2. Hampering development of technologies and/or capacity increases for the recycling of materials that are currently not recycled, but might be in the future,
3. Discouraging separation of currently recyclable materials from mixed waste stream and/or the development of more advanced separation technologies that could enable recycling of higher fractions of mixed waste streams in the future.

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[34] DEFRA (2011) Applying the Waste Hierarchy: evidence summary, Available from: https://www.gov.uk/government/publications/applying-the-waste-hierarchy-evidence-summary (Accessed on 1st December 2017)

This risk can be assessed by asking question 3 in the sustainability assessment framework: "Can the feedstock be reused or recycled?". However, answering this question is not trivial as there are several reasons why a particular waste stream may not be able to be recycled:

- The feedstock cannot technically be recycled
- The feedstock is too mixed or contaminated for re-use/recycling, or
- Re-use/recycling facilities are not available, for example they do not have spare capacity or are at a considerable distance from the source of the waste.

Only rarely do technical barriers preclude the recycling of a material – in some cases even plastic films and thermosetting plastics can be re-used or recycled[35,36] . However, the application of a strict "technical feasibility criterion" would make very few materials eligible for support, and could therefore miss an opportunity to divert some material from landfill or reduce greenhouse gases.

Economics are an important driver for recycling, since producers of recycled materials compete on the market with those produced from virgin (fossil) materials. The more advanced processing technologies, sorting steps, feedstock cleaning processes or long transport distances that are are involved in producing recycled materials, the higher the cost of producing recycled material, and hence the more likely it is that waste streams are sent to waste incineration or landfill instead.

An important policy dilemma is whilst withholding support for fuel production from a material is unlikely to encourage recycling of this material today, incentivising fuel production from this material may create a disincentive for recycling in the future, for example by reducing investment into R&D of sorting or recycling technologies. Increased competition for resource may result in transport fuel production undercutting other EfW facilities, and even recycling facilities: it has been estimated that if all residual waste infrastructure committed in 2017 was fully utilised then the maximum recycling rate achievable in 2030 would be only 63%.[37] Support for liquid fuels produced from waste should therefore be developed in close collaboration with waste management, recycling and circular economy policy to eliminate undesirable unintended consequences from this support. Undercutting the economic case for recycling is a key risk of supporting liquid fuel production from those feedstocks which could otherwise be recycled, particularly those such as plastics for which there is a clear policy objective to increase recycling rates.

In practice, the assessment of question 3 is likely to be very specific to each feedstock, and may even vary within a given feedstock type depending on where the material was sourced,

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[35] Axion Consulting (2012) for Wrap, Film reprocessing technologies and collection schemes, Available from: http://www.wrap.org.uk/sites/files/wrap/Film%20reprocessing%20technologies%20and%20collection%20schemes.pdf

[36] Recycled Plastic (n.d.) Thermoplastics vs. thermosetting plastics, Available from: http://www.recycledplastic.com/index.html%3Fp=10288.html (Accessed on 17th January 2018)

[37] Eunomia (2017) Residual waste infrastructure review, Issue 12, Available from: http://www.eunomia.co.uk/reports-tools/residual-waste-infrastructure-review-12th-issue/ (Accessed on 5th December 2017)

how contaminated it is etc. Therefore it is recommended that this assessment should occur on a case-by-case basis for each feedstock in a given plant. Moreover, if substantial amounts of a given feedstock are used for production of liquid transport fuels, DfT should review regularly whether this creates a ‘market’ for residual waste which disincentivises recycling.

When a fuel production process can result in some material recovery, for example the production of carbon black which can be recycled back into other products, or recovery of metals from process residue, this should also be taken into account.

It is advisable to make a distinction between consignments from planned supply chains (feedstock is produced on a continuous basis) vs “one-off” consignments (batches of a material that cannot be reused or recycled for specific ad-hoc reasons, such as contamination). For planned supply chains, fuel suppliers should provide information about the origin of the feedstock, as well as verifiable information about the reasons that feedstock cannot be reused or recycled.

Similar to the determination of “waste status” (section 3.2.2), DfT could collect information through a questionnaire in a process similar to the current biomass wastes and residues assessment process. Once approved, a supply chain should be re-tested periodically to ensure that the conditions of its original application persist. For one-off consignments under a certain size, it may be most effective to implement a fast-track questionnaire plus evidence approval system to keep administrative efforts low, but maintain the rigour of the waste hierarchy.

3.6 Risk that production and use of fuel leads to increased lifecycle GHG emissions

3.6.1 Risk description

GHG emissions are affected mainly by the **feedstock** and the **fuel production process**. In addition, the nature of the final **fuel** can influence its associated GHG emissions, either because of potential fuel leakages such as CH_4 emissions in the case of natural gas engines, or because of the conversion efficiency of the engine, which differs for fuel cells and conventional gasoline or diesel internal combustion engines.

Life cycle fuel GHG emissions comprise direct and indirect emissions. The direct emissions are those directly associated with producing the fuel and feedstock, and the inputs required for this. The indirect emissions are those not directly caused by the fuel production process, but caused by a change in the wider economy when that fuel is produced, and include:

- Increased GHG emissions caused by the use of alternative fuels or materials when feedstocks are diverted away from existing uses
- Increased release of CO_2 emissions resulting from extraction of a particular feedstock, for example if the use of CO_2 from volcanic/geothermal vents accelerates the release of CO_2

3.6.2 Methodology for assessing GHG emissions

In this study a methodology for assessing the GHG emissions from low carbon fossil fuels has been developed, based on a review of existing methodologies, which is given in Appendix E. The different nature of fuels produced from waste/by-product feedstocks, those which are produced from feedstock extracted specifically for liquid fuel production, and those which are produced from only CO_2 or water means that different methodologies are appropriate for each of these fuel types. These methodologies are given in sections 3.6.2.1 to 3.6.2.3.

3.6.2.1 For fuels produced from feedstock with zero energy content

Many RFNBO fuel production pathways can produce non-renewable fuels alongside the RFNBO in the same production process, for example if an electrolyser uses grid electricity supplied by electricity from both renewable and non-renewable sources.[38] Therefore for consistency of reporting, and to avoid loss or double-counting of emissions, the methodology adopted for non-renewable fuels where the feedstock has no energy content should be the same as that adopted for RFNBOs. A feedstock would here be defined as any substance which contributes atoms to the final fuel. This definition would therefore include hydrogen produced by electrolysis using fossil or biomass electricity, and methanol produced from CO_2 and fossil or biomass electricity.

We note that the current methodology allows fuels to be designated as part RFNBO, part fossil fuel according to the ratio of renewable: non-renewable energy entering the process (RTFO Year 11 draft Process Guidance Part 1). However the RFNBO and non-RFNBO portions of the fuel are required to take the same GHG intensity value, where the emissions are calculated based on all energy (both renewable and non-renewable) into the plant. This decision was made as both the renewable and non-renewable portion share the same process energy input. The result of this decision is that neither the renewable nor the non-renewable portion of part-RFNBO fuels produced from UK grid electricity will be likely to make a 70% GHG emission saving, so will not be supported under the RTFO. For example the GHG emissions of hydrogen produced by electrolysis using UK grid electricity (emissions factor currently 72.8 $gCO_2eq./MJ$) will likely be around 41 $gCO_2eq./MJ$ (including a 0.4 efficiency factor for hydrogen used in fuel cell engines) which does not provide a 70% GHG saving (see example calculations in Appendix F).

3.6.2.2 For fuels produced from feedstock which was extracted specifically for this purpose

The GHG emissions of fuels produced from feedstocks which are not wastes or co-products should be assessed using the methodology currently used in the FQD for default GHG values of conventional fossil fuels.

Default values are provided in the FQD for many of the fuels considered in this study. These default values must be used for reporting on the UK's compliance with the 2020 FQD target (actual value calculations are not allowed), and according to the current guidance under

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[38] The definition of a RFNBO excludes renewable electricity from biomass, so for the purposes of this discussion fuels produced from biomass electricity are included under the heading of non-renewable

consultation, should be used within the UK's GHG Mechanism for meeting this target. This limits the LCFFs that can be rewarded within the GHG Mechanism to those fuels which currently have a default value in the FQD legislation, or are in the process of acquiring one through the JRC.

After 2020, DfT could allow fuel suppliers to use these default values if they wish, but could also accept actual value calculations using the same methodology.[39] This would allow a wider range of fuels to be adopted, and would incentivise those fuel chains which do have default values to make improvements to their process which reduce their overall GHG emissions.

3.6.2.3 For fuels produced from feedstocks not extracted specifically for this purpose

This category of fuels refers to those produced from wastes. LCA studies of wastes often take as their functional unit 1 tonne of waste, and analyse the GHG emissions associated with different ways of dealing with that waste. This is a useful comparison to carry out, particularly for the purposes of designing waste-treatment policy, and could for example illustrate that one waste treatment method saves CO_2 compared with another waste treatment method. However the purpose of this study is to develop a GHG methodology for assessing the GHG emissions of the fuel produced from fossil wastes / by-products for comparison with other transport fuels, and assess potential participation in the same market.

The system boundary can be drawn either starting after the collection of the feedstock, or can also include the alternative use of the feedstock from which it was diverted.

Option A: System boundary after feedstock collection

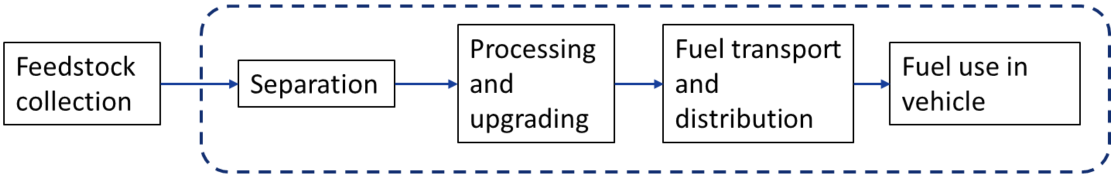

Figure 10 System boundary, GHG methodology option A

In this approach, emissions accounting starts after the point of collection of the feedstock at the first separation or processing stages. For waste fossil feedstocks, feedstock collection is assumed to be required regardless of the their use, so is not included within scope of the fuel GHG emissions. A key choice within this method is how to account for the embodied fossil carbon within the feedstock:

1. Always assign it to the transport fuel
2. Assign it to the transport fuel only if that carbon would not otherwise have been emitted to atmosphere.
3. Never assign it to the transport fuel

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[39] Some changes such as the use of exergy allocation instead of energy allocation, and a review of the credit for exported electricity might be appropriate, particularly if these factors are changed in the post-2020 biofuels methodology.

These three options are compared in Table 5.

Table 5 Comparison of options for assigning CO_2 emissions from embodied carbon in the feedstock, within GHG methodology option A

Option for assigning CO_2 emissions from embodied carbon in the feedstock	Rationale	Advantages	Disadvantages
Option A-1: Always assigned to transport fuel	The initial use of the feedstock material did not 'account' for that CO_2, it is emitted to the atmosphere through the fuel production and use phase, so the fuel must account for these emissions.	• Practically straightforward to implement • Ensures that fossil emissions which occur within the fuel production and use system are always fully accounted for. • Consistent with method for non-waste FFs	• Implies there are net carbon emissions even in cases where there are not. • Gives the same GHG emissions in the case that carbon is recycled and in the case that carbon is additionally released to the atmosphere. • This does not give any insight into which use of the feedstock would be the best use of resources
Option A-2: Assigned to transport fuel only if that carbon would not otherwise have been emitted to atmosphere.	The fuel accounts for emissions which are 'additional' to those which would have occurred anyway.	• Reflects the additional CO_2 emissions due to making transport fuels from waste/by-product fossil feedstock. • Assigning no emissions to carbon that would have been released in any case is the same principle as used in the RFNBO methodology	• Uncertainty in assessment of whether carbon 'would have been' emitted to the atmosphere. • Risk that even if carbon would have been emitted to the atmosphere it was not accounted for in any way in the original production system, so overall some emissions are not accounted for.
Option A-3: Never assigned to transport fuel	The material is a waste / by-product of another process, that process was responsible for the initial fossil fuel extraction and the emissions that eventually result from it, so the transport fuel should not account for these GHG emissions.	• Practically straightforward to implement	• This does not account for the additional fossil CO_2 emissions that could be caused by the production of transport fuels from feedstocks where that carbon was previously sequestered. • Risk that even if carbon would have been emitted to the atmosphere it was not accounted for in original production system, so overall some emissions are not accounted for.

We recommend that the most scientifically robust option is **Option A-2: assign the embodied carbon emissions to the fuel when it would not have been emitted to the atmosphere.** A time period for this assessment must be set, as it is likely that due to the global carbon cycle all carbon will eventually end up in the atmosphere. Given the urgency of tackling climate change, and in line with IPCC CO_2 emission factors, we suggest that this timeline should be 100 years. It should be noted that this is also the most challenging option to implement as it requires an assessment of whether the carbon in the feedstock would have been otherwise emitted to the atmosphere within this time period.

Option B: System boundary includes counterfactual use of feedstock

This approach treats the waste/by-product like a resource, recognising that using it for liquid fuel production diverts it from a (potential) alternative use and accounting for these indirect effects. If in its 'alternative use' scenario the fossil carbon was not released to the atmosphere then fossil carbon release to the atmosphere must be accounted for in the GHG emissions of the transport fuel. This approach is in line with that suggested by the JRC (2016) for the calculation of new default values under the FQD.

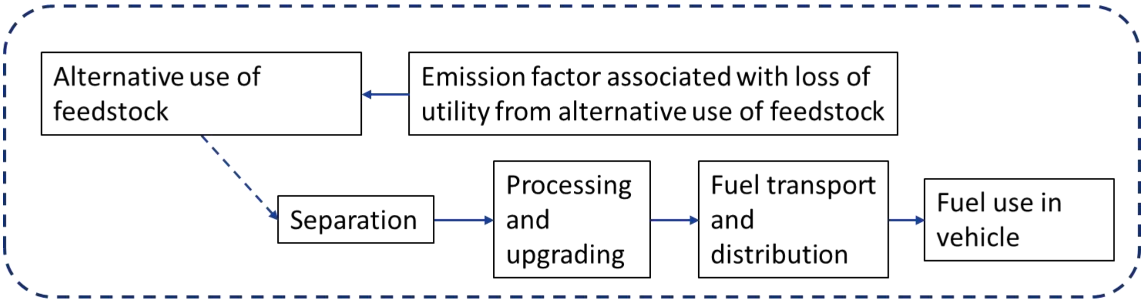

Figure 11 System boundary, GHG methodology option B

Advantages of this approach:

- Reflects net emissions to the atmosphere by including indirect GHG emissions
- In line with most recent JRC thinking on low carbon fossil fuels.

Disadvantages of this approach:

- Can be challenging to know and to provide reliable evidence on what the counterfactual use of a feedstock would have been. Even when this is known, it can be hard to know what will replace that lost utility (e.g. what type of electricity will replace that derived from waste plastic). Therefore assessment may not actually be very accurate or reflective of reality, and may be challenging to administer for DfT.
- Different from the treatment of biofuels under the RTFO, where indirect GHGs are not included in the fuel emissions factor.

Most appropriate methodology for fuels produced from waste / co-product feedstocks.

The GHG emissions of fuels produced from waste plastic, MSW and industrial CO gases have been analysed using methodology option A-2 and option B (see risk assessment of each of these fuel chains in Appendix F) to illustrate the impact of these different methodologies. Both of these options drive similar behaviours: diverting feedstock from a use where it was sequestered results in a fuel with high GHG emissions, whereas diverting feedstock from a use where it was emitted results in a fuel with lower GHG emissions.

Use of methodology A-1 or A-3, where all feedstocks, regardless of alternative uses, are treated the same does not capture the impact of diverting feedstock from one use or another. Therefore these methods would be useful for comparing a number of alternative waste treatment scenarios to understand which has the lowest associated GHG emissions, but are less appropriate for the aims of this study.

Many wastes/co-products, which might be processed into LCFFs, will already have an existing use, and diversion of the feedstock from that use will cause indirect GHG impacts. Therefore here methodology option B, which includes assessment of the counterfactual use of that feedstock, is recommended for assessing the GHG emissions of LCFFs produced from wastes or co-product feedstocks.

3.6.3 Summary of risk for all fuel types

The lifecycle GHG emissions of a potentially low-carbon fossil fuel are highly specific to the feedstock and production process of that fuel. Minor changes to the setup of similar production processes, for example in the fuels used to provide heat and power to the plant, can determine whether the fuel provides GHG savings compared to gasoline or diesel. Therefore all fuel routes carry the risk of not meeting the GHG threshold due to their **processing emissions**, as is the case for biofuels.

In Table 6 we have assessed the likelihood that, given typical conversion efficiencies, a fuel produced from a given **feedstock** will have higher GHG emissions than gasoline or diesel. This should be treated as indicative only: the GHG emissions of the final fuel also depend on processing emissions which cannot be generalised for a given feedstock. The GHG emissions associated with each feedstock depend on its production, indirect impacts associated with its use, which means that within each broad feedstock category (e.g. waste plastic) a wide range of GHG emissions is conceivable. Therefore the assessment given in Table 6 of the likelihood of fuel produced from a given feedstock not making GHG savings is dependent upon two factors: the GHG impacts associated with different feedstock origins or counterfactual situations, and how likely these different scenarios are to occur. For each feedstock these are discussed in more detail in Appendix F. Decarbonisation of transport fuel is a high priority for DfT, therefore if this risk occurs the impact is **severe** for all fuel chains.

Table 6 Summary of risk profile for specific fuel production routes. Criteria for assessment of severity and likelihood of risk occurring are outlined in Appendix B.

Feedstock	Likelihood of fuel increasing GHG emissions due to emissions associated with feedstock	Severity of risk if it does occur
Natural gas	🟧	🟥
Coal	🟥	🟥
Waste fossil plastics	🟧	🟥

Waste tyres	🟧	🟥
Mixed waste streams	🟧	🟥
Waste fossil liquids	🟧	🟥
Waste industrial CO gases	🟩	🟥
CO_2	🟧	🟥
Hydrogen (as a fuel)	🟩	🟥

3.6.4 How this risk is assessed

The mitigation of the risk of a fossil fuel increasing GHG emissions is achieved through question 4 of the sustainability assessment framework. The GHG emissions of each fuel chain should be assessed using the methodologies suggested in section 3.6.2.

Given that the GHG emissions of each fuel are very sensitive to the particular production process and feedstock that has been used in its production, DfT should assess each LCFF production process separately. Where a production process uses a number of different feedstocks, or feedstocks of different origin, then emissions should be also assessed for each feedstock type. Where the feedstock is anticipated to change over time, or the GHG emissions associated with that feedstock might change over time, then DfT should also assess the emissions from that fuel on an ongoing basis. For fuels supplied under the GHG mechanism before 2020 only the FQD default values can be used, so such fuels would be an exception to this recommendation.

The indicative GHG calculations given in Appendix F are intended to illustrate the choice between different methodologies, not for the purpose of assessing the GHG emissions of specific fuel chains.

How to assess the counterfactual use of a waste feedstock?

To use Method B for assessing the GHG emissions of a fuel derived from fossil wastes, knowledge of the use from which that feedstock is diverted is required. Some of this information is likely to have been collected by DfT in the earlier assessment of whether the feedstock is a waste (see section 3.2.2). However for some fuel types, particularly those which are from a ‘pool’ source such as traded RDF, it will be impossible to know the exact use from which that particular feedstock is diverted. For determining the counterfactual feedstock use there is therefore a hierarchy of preferred approach:

1. Producer can provide evidence as to the exact use the feedstock is diverted from. This is anticipated to be the case for all point-source feedstocks.
2. Producer provides evidence as to the marginal use of that feedstock within the relevant geographical area over which it is usually transported and traded. The emissions factor of the feedstock is calculated from the impact of diverting it from this marginal use.
3. Producer provides evidence as to all alternative uses of that feedstock within the relevant geographical area over which it is usually transported and traded, so that a weighted average emissions factor can be used.

As a substantial portion of the final fuel GHG emissions come from the indirect impacts of diverting the feedstock from its counterfactual use, a robust verification process should be in place to review this evidence.

3.7 Risk of increasing fossil fuel extraction or extending the lifetime of fossil fuel assets

3.7.1 Risk description

The UK has committed to challenging 2050 carbon reduction targets, which will require substantial transition away from fossil fuels. There is a risk that supporting any fossil fuel routes, even those which may have lower GHG emissions associated with them than conventional gasoline and diesel transport fuels, will continue to perpetuate fossil fuel supply chains and inhibit progress towards 2050 GHG reduction goals. Therefore, supporting such fuels may be considered a risk to long-term decarbonisation aims.

3.7.2 Summary of risk for all fuel types

The likelihood of LCFF production and use increasing fossil fuel extraction or extending the lifetime of fossil fuel assets is summarised in Table 7. This risk is assessed as moderately severe for DfT because there may be competing priorities such as the need for local jobs and energy security.

Table 7 Summary of likelihood and severity of specific fuel chains increasing fossil fuel extraction or extending the lifetime of fossil fuel assets.

	Likelihood of fuel production increasing fossil fuel extraction or extending the lifetime of fossil fuel assets	**Severity of risk if fossil fuel extraction increases or lifetime of fossil fuel assets extends**
Primary (non-waste) feedstocks	🟥	🟧
Waste feedstock (producer of waste gains from waste valorisation)	🟧	🟧
Waste feedstock (producer of waste not impacted by waste valorisation)	🟩	🟧

Non-waste feedstocks:

When non-waste feedstocks such as natural gas, coal and fossil electricity are used for the production of transport fuels, increased fossil fuel extraction will occur due to the additional use of these resources. However, as long as these fuels are replacing conventional gasoline or diesel in the market, overall there should be no net increase in fossil fuel extraction.

Nevertheless, support for these fuels supports fossil fuel infrastructure and may contravene wider UK decarbonisation objectives.

Waste feedstocks (producer of waste gains from waste valorisation):

There is a risk that providing support for some low carbon fossil fuels based on by-products (e.g. CO off gas from the steel industry) or wastes from industrial plants, extends the lifetime of fossil fuel assets or fossil fuel based production processes, by providing an additional revenue stream for the plant or reducing the plant's ETS payments[40] . This may discourage companies from seeking alternative non-fossil fuel sources, investing in alternative infrastructure or production processes, or making plant efficiency improvements which might reduce overall fossil fuel use. The extent to which this is likely to happen is highly uncertain.

Waste feedstocks (producer of waste not impacted by waste valorisation):

In cases where the producer of the waste does not benefit from valorisation of the waste, this risk is unlikely to occur, because the use or value of the waste has minimal impact on the materials chosen in production of a product.

3.7.3 How this risk is assessed

This risk is assessed through question 5 of the assessment framework, 'is the fuel in line with strategic decarbonisation of the UK economy'.

To understand whether the fuel chain poses a risk of increasing or supporting fossil-fuel based industries, DfT should establish which of the following three categories the fuel fits into:

(a) non-waste feedstock
(b) waste feedstock where the producer gains from waste valorisation
(c) waste feedstock where the producer does not gain from waste valorisation

In case (c) no further evidence would be required by DfT. In case (a) the risk is known and if DfT chooses to support these fuel types this risk must be accepted.

In case (b) further evidence may be required to establish whether support for fuel production from waste supports a fossil fuel industry, or industry use of fossil fuels in a manner that is inconsistent with UK decarbonisation targets. Evidence on the percentage of overall plant revenue that is anticipated to come from the feedstock compared to percentage of overall plant revenue that currently comes from the use of that waste could indicate whether this would provide substantial support to the plant. This should be considered in the context of wider UK policy (such as the phasing out of coal-fired power generation) to understand whether supporting the fuel might oppose existing UK decarbonisation strategy in other sectors.

Nevertheless, DfT should also weigh up the risk of supporting these fuels with the contribution they may make to wider DfT decarbonisation strategy of the transport sector, for example:

- Support for low-carbon fossil fuels may provide a greater incentive for increased production of fuel from mixed non-recyclable wastes, in line with circular economy and waste reduction goals,

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[40] Whiriskey, K., Wolthuys, J.V., for Bellona (2016) CCU in the EU ETS: risk of CO_2 laundering preventing a permanent CO_2 solution

by enabling support to be claimed for the whole portion of the fuel, rather than just the biogenic portion. This could result in (a) more biogenic waste being used, and (b) reduce energy use in separation of the biogenic from the non-biogenic fraction of waste.

- Support for some low-carbon fossil fuels may develop conversion technologies that can also process renewable feedstocks, therefore facilitating production and use of higher volumes of renewable fuels in the medium to long-term. For example development of the Fischer-Tropsch process supports production of diesel from both biogenic and non-biogenic feedstocks. Similarly, use of low-carbon fossil feedstocks may enable plant construction at a viable scale in areas where it would not be possible to reliably feed a plant on renewable resources alone, which could unlock potential for new renewable feedstocks, reduce renewable feedstock transport distances, or enable lower cost or higher efficiency conversion through increased plant scale.
- Whether a fuel is of strategic importance for long-term decarbonisation of UK transport, such as aviation fuel or diesel substitutes, which can reduce GHG emissions in sectors which are difficult to electrify.

3.8 Threshold for GHG emissions

Currently biofuels supplied under the RTFO must meet a minimum 70% GHG emissions saving compared to the fossil fuel comparator of 83.8 $gCO_2eq./MJ$, whilst not including indirect emissions in their GHG emission factor. This section provides an approach to setting a GHG threshold for LCFFs.

A GHG threshold is likely to be implemented for one of two reasons:

- Where there are uncertainties in GHG emission factor calculations, to ensure that some GHG saving is achieved.
- To ensure that the switch to a new fuel type results in substantial GHG emissions savings, in line with long term decarbonisation requirements of the sector.

Given the different nature of the three LCFF fuel types identified in the sustainability assessment framework, the different sustainability requirements that are imposed on them, and the different GHG calculation methodologies, it may be appropriate to apply different GHG thresholds.

In particular it should be noted that if the ‘counterfactual’ methodology (option B) is applied to waste-based fossil fuels, indirect GHG emissions of diverting the feedstock from an alternative use are also included in the fuel emissions factor. Therefore a 70% threshold, which is currently used for biofuels which do not include indirect emissions in their GHG intensity, may not be appropriate for waste-based fossil fuels calculated using this methodology. Moreover, indicative calculations (Appendix F) suggest that using method option B, only if MSW and waste plastic that has been diverted from energy recovery could fuels produced from these feedstocks meet a 70% threshold, and even with this alternative use it would be challenging for plastics to fuel chains and very challenging for MSW to fuel chains to meet a 70% savings threshold.

Currently, biofuels and RFNBOs are assessed on their carbon savings compared to the RED comparator (83.8 $gCO_2eq./MJ$) whilst fossil fuels are assessed against the FQD fossil fuel comparator of 94.1 $gCO_2eq./MJ$. If a GHG threshold for LCFFs is implemented, comparability with other renewable fuels is likely to be a priority in setting the most appropriate comparator.

4 Inclusion of LCFFs within UK and Ireland carbon calculator

Should DfT decide to support low carbon fossil fuels, the UK and Ireland carbon calculator could be modified so that fuel producers could make GHG calculations within this tool.

LCFFs produced from non-waste feedstocks would fit within the existing modules with minimal modification. Only the 'feedstock cultivation' module for biomass would need to be changed to calculate instead emissions from raw material extraction.

LCFFs produced from feedstocks which have no energy content would have a similar GHG methodology to RFNBO fuels, but this is quite different to the existing biofuel methodology used within the calculator. Therefore inclusion of these fuels within the calculator would likely require several new module types and a different underlying calculation methodology. If RFNBO fuels were already included within the calculator, which seems plausible given that they are shortly to be included within the RTFO, then the additional inclusion of LCFFs produced from feedstocks which have no energy content would require substantially less work.

LCFFs produced from waste-based feedstock would require some modification to the existing calculator, likely an additional or alternative module at the start of the chain to reflect the GHG emissions associated with the feedstock.

5 Conclusions

This study aimed to assess the sustainability impacts of low carbon fossil fuels, in order to understand whether they should receive government support. The scope included a wide range of fuels which could potentially be low-carbon: fuels produced from waste fossil feedstock, fuels produced from non-waste fossil feedstocks, and fuels produced from CO_2 or water and non-renewable energy (RFNBO-type fuels). The aims of the project were achieved through carrying out a broad landscape assessment of possible low carbon fossil fuel routes, developing a sustainability assessment framework, and assessing broad classes of fuels against this framework. Key sustainability and policy conclusions from the study are provided in this section.

Sustainability of low carbon fossil fuels

The main sustainability risks which could be presented by low carbon fossil fuels are the risk of making poor use of resources through contravening the waste hierarchy, and the risk of making low or even negative greenhouse gas savings compared to conventional fossil fuels. Existing fuel standards and emissions legislation means that in most cases LCFFs are unlikely to pose a severe risk to air quality compared to conventional gasoline or diesel or other alternative fuels.

Producing liquid fuels with a feedstock that is diverted from landfill or energy from waste does not contravene the waste hierarchy, as liquid fuel production comes higher in the waste hierarchy than landfilling that material, and at an equal level to other forms of energy recovery such as energy from waste. However there is a risk that incentivising use of a feedstock for liquid fuel production will undercut the economic case for future measures or investments to increase recycling. Therefore policy support for waste-based fossil fuels should be closely integrated with recycling policies to avoid unintended consequences of incentivising liquid fuel production.

A number of approaches to calculating the GHG emissions of low-carbon fossil fuels have been reviewed. Calculation of the GHG impact of RFNBO-type fuels (made from CO_2 or water and non-renewable electricity) and non-waste fossil fuels should be in line with existing DfT methodology for these fuels. Illustrative calculations using these methods demonstrate that some RFNBO-type fossil fuels, such as hydrogen produced from natural gas or nuclear-derived electricity, and some non-waste fossil fuels, such as natural gas used in vehicles or hydrogen produced from natural gas, could reduce GHG emissions compared to conventional gasoline or diesel. In certain cases, for example when CCS is used in the production process, these emissions savings could be greater than 70% compared to conventional gasoline or diesel.

The most robust approach to calculating the GHG impacts of waste-based fossil fuels would account for the indirect emissions associated with diverting that feedstock from an existing use. In cases where the feedstock would have been sequestered, for example in landfill, the GHG emissions of the fuel are likely to be similar to, or higher than, those from conventional gasoline or diesel. For feedstocks that would have been combusted, the net emissions of the fuel can vary from substantially lower than conventional fossil fuels to substantially higher, depending on what replaces the waste as a fuel or what energy sources replace the electricity and heat from the waste-to-energy plant. Those feedstocks which would have alternatively been incinerated with no energy recovery, such as flared waste gas and hazardous liquids, have the lowest GHG emissions and would likely be able to meet a 70% GHG saving threshold.

Whilst a 70% GHG saving threshold is applied to biofuels, it is not necessarily appropriate to apply the same GHG saving threshold to low carbon fossil fuels. In particular, the GHG methodology proposed here for waste-based fossil fuels includes the indirect emissions from diverting that feedstock from an existing use, whereas indirect emissions are not included within the GHG assessment for biofuels.

Policy support for low carbon fossil fuels

This study has shown that some low carbon fossil fuels can sustainably reduce GHG emissions, potentially with additional benefits such as a reduction in air pollutants and diversion of waste from landfill. Given that the future production of advanced biofuels is likely to be limited by the availability of sustainable volumes of waste biomass and the early commercialisation status of some of the production technologies, low carbon fossil fuels could provide a valuable contribution towards the reduction of GHG emissions in the transport sector. Indeed they could even facilitate the longer-term transition to alternative renewable fuels, for example use of natural gas in engines may facilitate the uptake of more biogas, and use of fossil hydrogen may promote the construction of the necessary infrastructure for renewable hydrogen in the longer-term. Robust sustainability criteria should be implemented if support is provided by DfT. Moreover, support for non-waste low carbon fossil fuels could support continued fossil fuel use so should be carefully considered in the context of wider government decarbonisation policy.

Several of the technologies for producing low carbon fossil fuels are still pre-commercial, therefore if DfT decides to support low carbon fossil fuels, market pull policies such as the existing RTFO mechanism, and push policies such as competitions or grants would both be appropriate. Market-based policies are likely to be most effective for fuels which are commercial or close to commercialisation. For technologies which are at an earlier stage of development, competitions or grants may be needed to achieve early deployment of these fuels. Such support, for a technology route which is not yet commercial, could be given by DfT where the fuels have particular strategic importance for long-term decarbonisation of the UK transport sector. Nevertheless, market based support for these fuels is also needed to give investor confidence, as investment relies on the future market prospects rather than one plant alone.

To 2020, market-based support for low carbon fuels is separated into support for renewable fuels (Renewable Transport Fuel Obligation) and support for other low-carbon fuels (Greenhouse Gas mechanism). Currently only fuels that have defaults in the FQD legislation can count towards the GHG mechanism. DfT could widen the range of fuels supported under the GHG mechanism by allowing suppliers of fuels which do not currently have a GHG default in the FQD legislation to gain GHG credits, using the methodology suggested in this study. However few low carbon fossil fuels are expected before 2020 which do not have a GHG default value in the FQD legislation so this may have a limited impact.

Post 2020 there are two main options for supporting low carbon fuels: a) keep support for renewable fuels and non-renewable fuels separate, which could enable a greater reward to be given to renewable fuels, or b) bring renewable and non-renewable fuels together under a GHG-based target such as that already used by Germany, with strict sustainability criteria for all fuels. If approach b) is adopted, DfT should ensure that inclusion of low carbon fossil fuels within a support scheme does not push out renewable fuels, especially where these are less established and may not be able to compete economically. In addition, the more fuel types, and the greater diversity of fuel types that are included within the same support scheme, the more difficult it is for producers to assess the potential supply and therefore the price, which can lead to reduced investor confidence.

Appendix A Technology readiness level scale

As used by the European Commission

Technology Readiness Level	Description
TRL 1.	basic principles observed
TRL 2.	technology concept formulated
TRL 3.	experimental proof of concept
TRL 4.	technology validated in lab
TRL 5.	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6.	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7.	system prototype demonstration in operational environment
TRL 8.	system complete and qualified
TRL 9.	actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Appendix B Assessing severity and likelihood of risk

For each sustainability risk identified, the severity and likelihood of this risk occurring for each feedstock or particular fuel has been assessed. A summary is presented in the main body of the report, and the detail on that assessment for each pathway is presented here.

The assessment of the severity of each risk of based on:

- Red = materialisation of this risk poses a severe threat to human health or the environment
- Orange = materialisation of this risk poses a moderate threat to human health or the environment
- Green = materialisation of this risk poses minimal threat to human health or the environment

The assessment of the likelihood of each risk of based on:

- Red = materialisation of this risk is highly likely for this fuel / feedstock
- Orange = materialisation of this risk is moderately likely for this fuel / feedstock
- Green = materialisation of this risk is not likely for this fuel / feedstock

Appendix C Risk that use of fuel will increase local air pollutants

LNG, CNG and SNG

Liquefied natural gas (LNG) and compressed natural gas (CNG) are two ways of delivering natural gas into an engine and therefore have similar pollutant emission profiles. Synthetic natural gas (SNG) could be used in either of these forms in engines. A standard exists for natural gas and biomethane used in vehicles (EN 16723)[41]. LNG and CNG are primarily used either in dedicated spark ignition engines, or in dual fuel engines which may be manufactured specifically for this process or retrofitted to existing engines. As of May 2017 the only natural gas engine that had met the EURO VI emissions standard is the dedicated stoichiometric engines, although other technologies such as the dual fuel high-pressure direct injection system are expected to meet these criteria in the future.[42]

Emissions of specific pollutants from a range of vehicle types operating on LNG and CNG were investigated in a recent study by the LowCVP.[43]

LPG

LPG used in the automotive sector is covered by CEN standard EN 589, and is mainly used in dedicated (factory fitted or converted) LPG engines but can also be used in dual fuel engines.

More information on specific pollutants emitted through the use of LPG in engines is available from the LowCVP (2017).

Synthetic gasoline and diesel

Synthetic gasoline and diesel are likely to be supplied into the UK blended into conventional gasoline or diesel to meet the existing standard for these fuels.[44] Compliance with these standard mitigates the risk of these fuels creating adverse air quality impacts, but DfT may wish to investigate further the impact of these novel fuels on emissions of non-regulated pollutants.

If synthetic gasoline or diesel are supplied outside of the existing standard, for example a private supply from a fuel producer to a HGV fleet operator, there is a higher risk of these fuels creating adverse air pollution impacts.

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[41] CEN (2017) Natural gas and biomethane for use in transport and biomethane for injection in the natural gas grid, Available from: https://standards.cen.eu/dyn/www/f?p=204:32:0::::FSP_ORG_ID,FSP_LANG_ID:853454,25&cs=1A6E2885FFA69ED2A8C4FA137A6CEF3DA (Accessed 4th December 2017)

[42] ETI (2017) Natural gas pathway analysis for heavy duty vehicles, Available from: http://bit.ly/2zNxfRR (Accessed on 28th November 2017)

[43] Department for Transport and LowCVP (2017) Emissions testing of gas-powered commercial vehicles, Available from: http://www.lowcvp.org.uk/assets/reports/LowCVP%202016%20DfT%20Test%20Programme%20Final%20Report.pdf (Accessed on 28th November 2017)

[44] EN228 for gasoline and EN590 for diesel

Jet fuel

There are two types of synthetic aviation kerosene within scope of this study – synthetic paraffinic kerosene (SPK) produced from Fischer Tropsch synthesis, which can be blended up to 50% in conventional aviation kerosene, and SPK produced from an alcohol to jet process. This can currently be blended up to 30% in kerosene if produced from sugars, and pathways from synthetic alcohol are in the process of certification. [45]

Aircraft have no combustion after-treatment systems so their emissions profile is very sensitive to the fuel composition which, while tightly regulated in terms of composition, is generally less tightly regulated in terms of its environmental impact. For example sulfur limits for aviation fuel are 3000ppm compared to 10ppm for road diesel in the UK. Therefore novel jet fuels could pose a substantial risk to air quality, due to the lack of pollutant emissions regulations in this sector. On the other hand the lack of existing regulation in the aviation sector could also provide opportunity for novel jet fuels to reduce non-GHG pollutants. The synthetic jet fuels within scope of this study tend to have lower sulfur and aromatics content, which lowers SOx and particulate matter emissions compared to conventional refinery kerosene. [46]

Methanol, ethanol and butanol

Alcohols are typically, but not exclusively, blended into gasoline at limited levels in order to meet the EN228 gasoline standard. Compliance with this standard mitigates the risk of these fuels having an adverse impact on local air pollution in new and existing vehicles.

For higher alcohol blends such as E85 there is currently a reference standard and a draft CEN standard. E85 was briefly commercially available in the UK, (mainly for racing applications) but today this blend is more likely to be supplied into a captive fleet, representing a very small proportion of total UK fuel supply, therefore limiting the extent of this risk.

Hydrogen

When hydrogen is used in a fuel cell, the only tailpipe emission is water. Consequently, the use of hydrogen in a fuel cell is pollutant free at the point of use.

Limited work has been conducted on the use of hydrogen in internal combustion engines, but it is anticipated that particulate matter and NOx may be reduced when the optimum combustion and after-treatment strategies are used.

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[45] CAAFI (2017) Commercial aviation alternative fuels initiative, Available from: http://www.caafi.org/resources/faq.html (Accessed on 4th December 2017)

[46] Lobo, P., Hagen, D.E., Whitefield, P.D. (2011) Comparison of PM Emissions from a Commercial Jet Engine Burning Conventional, Biomass, and Fischer–Tropsch Fuels, *Environ. Sci. Technol.*, 2011, 45 (24), pp 10744–10749, Available from: http://pubs.acs.org/doi/abs/10.1021/es201902e

Appendix D Risk of feedstock not meeting the waste hierarchy

Waste fossil plastic

The majority of plastic contained within UK mixed waste stream is not separated, and ends up in landfill or energy from waste (Appendix F, Figure 14). Therefore a feedstock that is composed only of waste plastic will likely have been derived from a specific plastic waste collection scheme, having undergone some sorting to remove more readily recyclable plastics.

Most types of plastic can technically be recycled, either into the same product (closed-loop recycling) or into alternative products (open-loop recycling). Even thermosetting plastics for example, which cannot be melted into new products, can still be re-used in other applications such as re-manufacture into carpet underlay, or as a mixture in the production of non-structural lightweight concrete.[47]

However, there are other reasons, aside from technical ability to recycle plastics, why plastics might not be able to be recycled[48]:

- Collection
    - Limited recycling infrastructure
    - Collection is widely dispersed and small in scale
    - Complex shipping regulations may limit transportation
- Processing
    - Lack of knowledge and skills of processor
    - Technological limitations of sorting and reprocessing
    - Restrictions on contaminates
    - Value chain partners are not connected (e.g. recyclers may be small and not global players)
    - Underdeveloped market for recycled plastics
- Economics
    - Technologically advanced processes or the number of processing steps may prove too costly for the production of recycled plastics that can compete against virgin fossil plastics on the market.

Using a type of plastic that cannot be recycled for liquid fuel production would not contravene the waste hierarchy. However DfT should note that developments in plastic recycling technology, for example improvements in black plastic separation[49], may change over time the definition of what material can be recycled.

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[47] Panyakapo, P., Panyakapo, M. (2008) Reuse of thermosetting plastic waste for lightweight concrete, *Waste Management*, 28(9), 1581-1588

[48] Vlugter, J. for the Circular Economy 100, Ellen MacArthur Foundation and other partners (2017) Scaling recycled plastics across industries, Available from: https://www.ellenmacarthurfoundation.org/assets/downloads/ce100/Scaling-Recycled-Plastics-across-Industries.pdf (Accessed on 21st September 2017)

[49] Waste Management World (2017) Roadmap to Better Recycling for Black Plastics Launched, Available from: https://waste-management-world.com/a/roadmap-to-better-recycling-for-black-plastics-launched (Accessed on 1st December 2017)

Given the recent tightening legislation from China regarding the export of plastic for recycling[50], in the short term there may be a larger volume of plastic within the UK which would have previously been exported to China.[51] There are fears that this material could now be landfilled or combusted for energy instead of recycled, potentially increasing the volume of waste plastic available for sustainable liquid fuel production. However, industry opinion seems to be that more of this material could be recycled if the quality of it can be improved, for example through improved segregated collections, sorting and decontamination. There is a risk that creating an incentive for such materials to be transformed into liquid fuels, means that the economic case for investments in improvements in the recycling chain is less robust.

Therefore while for all plastics there is a risk of contravening the waste hierarchy, whether this is actually the case depends on the specific characteristics of the type of plastic in question, within a specific time frame and geographic limitation. Given these considerations, waste fossil plastic feedstocks have a moderate risk of not meeting the waste hierarchy.

Waste tyres

Waste tyres are likely to be partially biogenic and partially fossil, depending on the exact composition of the rubber. Only the fossil portion of the tyre is within scope of this report, although in reality the natural and synthetic components are distributed throughout the material and would not be separated.

Waste tyres can be re-treaded, re-used or recycled, or can be used for energy recovery, primarily in cement kilns in the UK. Only bicycle tyres and those with an outside diameter above 1.4m are allowed to go to landfill in the EU[52], although this may be higher in other countries.

Data from the DEFRA used tyres working groups (Figure 12) demonstrates the fate of all used tyres in the UK in 2016, grouped as re-use (blue), export (red), recycling (green) or energy recovery (orange). DEFRA consider that 23% of the mass of used tyres sent to cement kilns is 'recycling' as the metal is incorporated into the cement clinker. The fate of exported tyres is unknown, but correspondence with the used tyres working group suggested that while some of the exported tyres would be re-used, a significant portion would be used for energy recovery.

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[50] Lets Recycle (2017) Government 'looking into implications' of China restrictions, Available from: https://www.letsrecycle.com/news/latest-news/government-looking-china-restrictions/

[51] Resource (2018) EAC launches special inquiry into effects of China waste ban, Available from: http://resource.co/article/eac-launches-special-inquiry-effects-china-waste-ban-12351 (Accessed on 18th January 2018)

[52] DEFRA (2010) Environmental Permitting Guidance - The Landfill Directive, Available from: https://www.gov.uk/government/publications/environmental-permitting-guidance-the-landfill-directive (Accessed on 1st December 2017)

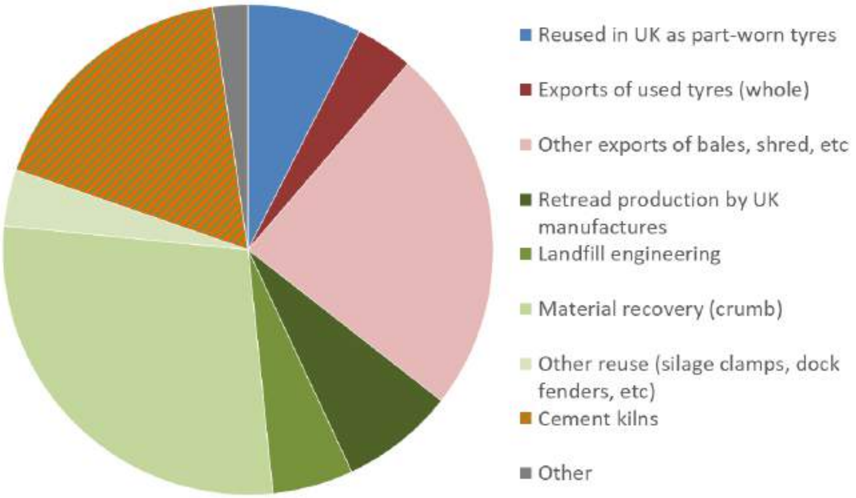

Figure 12 Fate of used tyres in the UK, grouped according to classification used by DEFRA as re-use (blue), export (red), recycling (green) or energy recovery (orange)

Other estimates suggest that across Europe the proportion of used tyres used for energy recovery may be higher, around 50%.[53]

Therefore there is a moderate risk that use of waste tyres for liquid transport fuel production diverts them from a use higher up the waste hierarchy.

Mixed waste streams

It is possible to separate out glass, plastics and metals for recycling from residual waste in material recycling facilities (called wet or dirty MRFs) [54,55]. For example near infra-red sorters (NIR) can produce streams of recyclable plastic from mixed waste streams.[56] The waste left over after recyclables have been removed is known as 'residual waste'.

It is also possible to process waste using intermediate technologies such as mechanical heat treatment (MHT) which includes autoclaving, and mechanical biological treatment (MBT). Mechanical heat treatment uses mechanical and thermal (including steam) technologies to separate a mixed waste stream into component parts, to sanitise the waste, and to reduce its moisture content.[57] MBT refers to a combination of processes, generally involving separation and biological treatment of waste, although in some systems minimal separation is implemented.[58] A variety of

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[53] European tyre and rubber manufacturers' association (2015) End-of-life tyre report 2015, Available from: http://www.etrma.org/uploads/Modules/Documentsmanager/elt-report-v9a---final.pdf (Accessed on 23rd October 2017)

[54] Defra (2011) Applying the waste hierarchy: evidence summary, available from: https://www.gov.uk/government/publications/applying-the-waste-hierarchy-evidence-summary

[55] For example, http://cawleys.co.uk/good-waste-management-practices/mrf/

[56] Wrap (2010) Plastic Fantastic, Available from: www.wrap.org.uk/sites/files/wrap/Case%20Study%20-%20Smallmead%20MRF.pdf, Accessed on 21st September 2017

[57] DEFRA (2013) Mechanical heat treatment of municipal solid waste, Available from: https://www.gov.uk/government/publications/mechanical-heat-treatment-of-municipal-solid-waste, Accessed on 21st September 2017

[58] DEFRA (2013) Mechanical biological treatment of municipal solid waste, Available from: https://www.gov.uk/government/publications/mechanical-biological-treatment-of-municipal-solid-waste, Accessed on 21st September 2017

different plant configurations for these techniques are possible, but both MHT and MBT generally produce a high calorific value waste stream termed refuse derived fuel (RDF) or solid recovered fuel (SRF), with the recyclable material already separated out. If RDF or SRF used in liquid fuel production have already had recyclables removed then their use is in accordance with the waste hierarchy. The main alternative use of RDF is in production of power, heat or both, including in cement kilns, which is at the same level in the waste hierarchy as production of liquid fuels.

Given these considerations, mixed waste stream feedstocks have a moderate risk of not meeting the waste hierarchy.

Waste fossil liquids

Waste fossil liquids are often hazardous and are likely to be either disposed of or used to produce secondary liquid fuel (SLF) for energy recovery. Therefore using these materials for fuel production is unlikely to contravene the waste hierarchy.

Given these considerations, waste fossil liquids feedstocks have a low risk of not meeting the waste hierarchy.

Industrial waste CO gases

In general industrial CO gases are either flared, which is disposal under the waste hierarchy, or combusted to produce heat and/or power. Therefore in both cases diverting the CO gases to fuel production would not contravene the waste hierarchy. In theory CO can be used as a feedstock for the chemicals industry, but the concentration and purity of waste CO gas produced by industrial processes makes this unlikely.

Given these considerations, industrial waste CO gas feedstocks have a low risk of not meeting the waste hierarchy.

Appendix E Review of GHG accounting approaches

GHG assessments of fuels produced from fossil wastes or by-products are not widespread, therefore here examples from Argonne national laboratory (Benavides, 2017) and the California Air Resources Board (Unnasch, 2015) are reviewed, along with the guidance provided by the Joint Research Commission (JRC) of the European Union for the calculation of default values under the FQD (JRC, 2016)

For each approach we outline below:

- Short description of the approach, including aims and scope
- System boundary, including whether 'alternative' use of waste feedstock is considered and if so how this is dealt with.
- How allocation of emissions amongst products and co-products is conducted

Californian Air Resources Board (CARB)

Description

The Californian Air Resources Board use the GREET model to certify fuel chains, and assess each chain on a case-by-case basis. They have so far only certified one fuel which uses waste fossil material: the MSW to FT diesel fuel pathway submitted by Fulcum Bioenergy. Therefore the methodology used to assess this particular fuel chain is reviewed here, based on the document submitted alongside the 2B application for this process.[59]

System boundary

The system boundary includes both the biogenic and fossil portion of the MSW, and runs from the delivery of MSW to the plant, through the fuel production process and fuel use in the vehicle. An emissions credit is given to the fuel for avoided landfill emissions for the biogenic portion of the waste. No burden is given to the fuel for the 'avoided sequestration' of fossil carbon that now does not enter landfill. The emissions from fuel combustion and CO_2 vented during the production process are also added to the total.

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[59] Unnasch. S. (2015) Avoided Life Cycle GHG Emissions from MSW Disposal, Life Cycle Associates, Report No. LCA6060.120.2015, Prepared for Fulcrum BioEnergy, Available from: https://www.arb.ca.gov/fuels/lcfs/2a2b/apps/ful-ftd-rpt-123015.pdf (Accessed on 22nd November 2017)

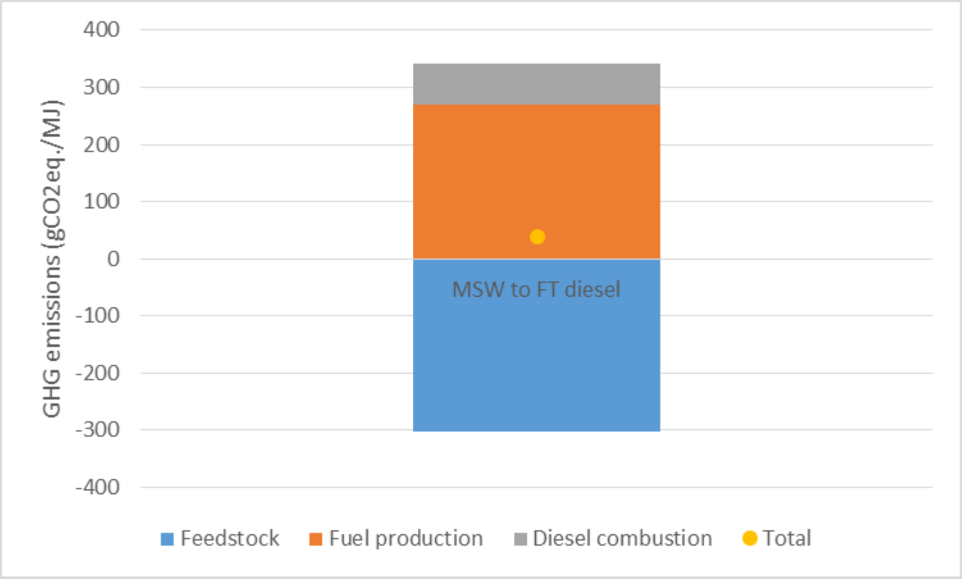

Figure 13 GHG emissions of MSW to FT diesel route as submitted to CARB (Unnasch, 2015)

Allocation

This is not addressed by Unnasch (2015).

Benavides (2017)

Description

Benavides et al. (2017) of the Argonne National Laboratory in the USA carried out a GHG assessment of a production route producing liquid transport fuel (diesel) from non-recycled plastics.

System boundary

The system boundary for the study begins with waste collection and shipping to a material recovery facility, includes all aspects of fuel production, and the fuel use phase. The feedstock is assumed to have zero emissions at the point of collection, and emissions from the combustion of the fuel are taken into account. The functional unit of this analysis is 1MJ of diesel, and the emissions of 1MJ of plastic- derived diesel are compared to 1MJ of crude-oil derived diesel.

In order to compare the environmental impacts of the plastic-to-fuel pathway with the conventional waste disposal pathway that it is displacing, an additional analysis is carried out using the same system boundary but with a functional unit of 1 tonne of waste.

Allocation

Three different allocation methods are investigated in this study: displacement, energy allocation and market value allocation. Energy allocation was used as a base case technique because all products in the system were energy products. The emissions factor of the diesel was lowest with displacement, followed by energy allocation and highest with market-based allocation of emissions to co-products. The GHG emissions of diesel with market allocation were up to approximately 10% higher than the GHG emissions of diesel with energy allocation.

JRC (2016)

Description

In 2016 the JRC put forward guidelines for calculating the GHG emissions associated with low-carbon fossil fuels and renewable fuels of non-biological origin, for the purposes of calculating default values for these fuels under the FQD legislation. The methodology is generally consistent with that laid out in Annex IV of the FQD / Annex V of the RED.

System boundary

The approach taken depends on whether the input is **elastic** or **rigid.** Elastic feedstocks are defined as those for which supply can expand to satisfy additional demand, for example a commodity such as natural gas, in which case attributional LCA is used. A rigid feedstock is defined as one where the supply of the input cannot be expected to expand to meet demand, such as MSW. The GHG intensity of a rigid feedstock is assessed based on the GHG impacts of removing a quantity of that material / energy from its current use. If the feedstock would have had a productive use then the GHG emissions of providing that service / product by an alternative resource are included in the rigid feedstock emission factor.

Allocation

Allocation of emissions to co-products is not explicitly addressed in this guidance from the JRC. In the few cases where it was required, allocation was done on an exergy basis.

Existing DfT biofuels methodology

Description

The existing method that DfT uses for calculating the GHG emissions associated with biofuels is based on the method prescribed in the Renewable Energy Directive legislation.

System boundary

The system boundary includes biomass cultivation and harvesting, fuel production, and fuel use. Because the carbon in the system is biogenic, emissions from fuel combustion and any CO_2 released as part of the fuel production process are assumed to be zero in terms of their GHG impact.

When biomass wastes or residues are used for fuel production, the system boundary starts at the point of collection of the waste. Emissions from avoided alternative uses of these wastes are not included.

Allocation

Energy allocation is used, except in the case of excess electricity produced by feedstocks which are not co-products of the system (except for agricultural crop residues) for example excess electricity produced from on-site natural gas CHP, where the fuel is given an emissions credit for displaced electricity.

Existing DfT RFNBO methodology

Description

DfT has put forward a methodology for calculating the GHG emissions of RFNBOs in the RTFO guidance documents which are currently under consultation.

System boundary

The system boundary of this methodology includes emissions from the extraction / collection of raw materials, all emissions associated with fuel production, and the emissions from the fuel in use.

Allocation

As for biofuels, energy allocation is proposed, except in the case where excess electricity is produced by cogeneration, in which case a credit is given for avoided generation of an equal amount of electricity using the same fuel.

Appendix F Risk that production and use of the fuel will lead to increased lifecycle GHG emissions

Fuel produced from natural gas

In most cases, transport fuels produced from natural gas are likely to have emissions similar to those from conventional gasoline or diesel.

Indicative values are given in the FQD Implementing Directive[60] for the emissions factors of fuels produced from natural gas (Table 8), illustrating that their emissions factors are slightly lower than those of the fossil fuel comparator[61]. A recent study from the ETI (2017)[62] explores in more detail the impact of different natural gas upstream emissions, transportation, distribution, dispensing and vehicle use scenarios. They conclude that LNG and CNG have the potential to reduce greenhouse gas emissions on a well-to-motion basis by 13% and 20% respectively in dedicated engines and by 16% and 24% respectively for dual-fuel HPDI engines. However they also note that methane slip, which can be particularly problematic in retrofit engines, can result in GHG emissions that are worse than the diesel comparator. Given this variability in the GHG emissions, it is assessed in Table 6 that natural gas pathways are moderately likely to increase lifecycle GHG emissions compared to the fossil comparator.

Use of CCS in liquid fuel production has the potential to significantly reduce the GHG emissions of the final fuel. While use of CCS is not widespread globally there are some facilities operating today. For example Air Products in Texas and Shell in Alberta currently carry out hydrogen production from natural gas with CCS.[63]

Table 8 Average life cycle greenhouse gas intensity values for fuels produced from natural gas (Default values from FQD Implementing Directive)

Raw material source and process	**Fuel placed on the market**	**GHG intensity of fuel (gCO_{2eq}/MJ)**	**GHG intensity of fuel (gCO_{2eq}/MJ)**
Natural gas (EU mix)	Compressed natural gas in a spark ignition engine	69.3	94.1
Natural gas (EU mix)	Liquefied natural gas in a spark ignition engine	74.5	94.1
Any fossil sources	Liquefied petroleum gas in a spark ignition engine	73.6	94.1

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[60] Council Directive (EU) 2015/652

[61] In this section of the study these emissions factors from the FQD Implementing Directive will be used for comparison of potential low-carbon fossil fuels with conventional gasoline or diesel, noting that these are slightly higher than the fossil fuel comparator used in the RED, 83.8gCO_{2eq}/MJ

[62] ETI (2017) Natural gas pathway analysis for heavy duty vehicles, Available from: http://bit.ly/2zNxfRR (Accessed on 28th November 2017)

[63] Global CCS Institute (2017) Projects Database, Available from: https://www.globalccsinstitute.com/projects/large-scale-ccs-projects (Accessed on 21st October 2017)

Natural gas using steam reforming	Compressed hydrogen in a fuel cell	104.3	94.1

If natural gas that is currently flared is used for fuel production, then the emissions from its combustion could be assumed to have occurred anyway in the counterfactual case. If this is taken into account, the GHG impacts of the gas feedstock would be low.

However, several aspects complicate the accurate assessment of the GHG impacts of using associated natural gas for fuel production:

- Reductions in associated gas flaring can also count as upstream emission reductions (UERs) to contribute to the 2020 FQD target, which means that there is a risk of double-counting these emissions savings.
- Given that globally natural gas flaring is decreasing, and significant efforts are being made and supported by multilateral donors to reduce associated gas flaring, it is likely that many producers will soon implement methane capture or other means of reduced production. If this is likely to occur without government subsidy then this reduces the case for UK government supporting its use for fuels today.

Therefore we would recommend that flared gas reduction / use should be considered as a UER rather than being able to be counted as a 'waste' feedstock for liquid fuel production.

Fuel produced from coal

Transport fuels produced from coal are likely to have emissions substantially higher than those from conventional gasoline or diesel. Use of CCS could reduce these emissions, potentially so that the fuel overall has lower GHG emissions compared to gasoline or diesel (Table 9). However there are no known commercial coal to liquids plants with CCS operating today. Demonstration-scale CCS was carried out at the Shenhua Group coal-to-liquids plant in China. Also a large-scale coal-to-liquids plant with CCS is planned for the 2020's in the Ningxia region of China,[64] and a coal to hydrogen plant including CCS is planned for Australia.[65] Given the early stage of these CCS technologies and isolated implementation, fuels produced from coal are assessed as highly likely to have increased lifecycle GHG emissions compared to conventional gasoline or diesel in summary Table 6.

Table 9 Average life cycle greenhouse gas intensity values for fuels produced from coal (Default values from FQD Implementing Directive)

Raw material source and process	Fuel placed on the market	GHG intensity of fuel (gCO_{2eq}/MJ)
Coal	Compressed hydrogen in a fuel cell	234.4

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[64] Global CCS Institute (2017) Projects Database, Available from: https://www.globalccsinstitute.com/projects/large-scale-ccs-projects (Accessed on 21st October 2017)

[65] ChEnected (2017) Kawasaki Industries Wants to Make Dirty Lignite Coal Useful and Clean, Available from: https://www.aiche.org/chenected/2017/04/kawasaki-industries-wants-make-dirty-lignite-coal-useful-and-clean (Accessed on 28th November 2017)

Coal with carbon capture and storage of process emissions	Compressed hydrogen in a fuel cell	52.7

Fuel produced from waste fossil plastic

Summary

The GHG emissions associated with using waste fossil plastics as a feedstock depend on the use from which that plastic is diverted:

- Diversion of plastic from landfill or recycling results in high GHG emissions associated with the feedstock.
- Waste plastic diverted from combustion with energy recovery can have GHG emissions ranging from low to high, depending on the energy that replaces the plastic.
- Waste plastic diverted from combustion without energy recovery would be likely to have low GHG emissions

Plastic used to make low carbon fossil fuels, which is likely to be diverted from either landfill or energy from waste in the UK, if it cannot be diverted from recycling due to the sustainability assessment framework, generally has emissions similar to or lower than conventional fossil fuels, except in some specific cases such as plastic use in cement kilns.

Most likely fate of waste fossil plastic in the UK

Wrap and Valpak[66] carried out a study in 2016 into the fate of all waste plastic arising in the UK from both household and commercial sectors. They concluded that of the plastic that was collected specifically for recycling, reuse and recovery, 28% was recycled in the UK, 59% was exported (ostensibly for recycling, but in reality this is very hard to monitor)[67] and 13% was sent to energy from waste. Of the plastic in residual waste, 56% was treated in an energy from waste plant, 37% was sent to landfill and 7% was treated by mechanical biological treatment (MBT). Figure 14 summarises the fate of all waste plastic in the UK, including both the plastic collected specifically for recycling, reuse and recovery, and the plastic in residual waste.

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[66] Wrap and Valpak (2016) Plastics spatial flow, an assessment of the quantity of un-recycled plastic in the UK

[67] Velis C.A. (2014). Global recycling markets - plastic waste: A story for one player – China. Report prepared by FUELogy and formatted by D-waste on behalf of International Solid Waste Association - Globalisation and Waste Management Task Force. ISWA, Vienna, September 2014.

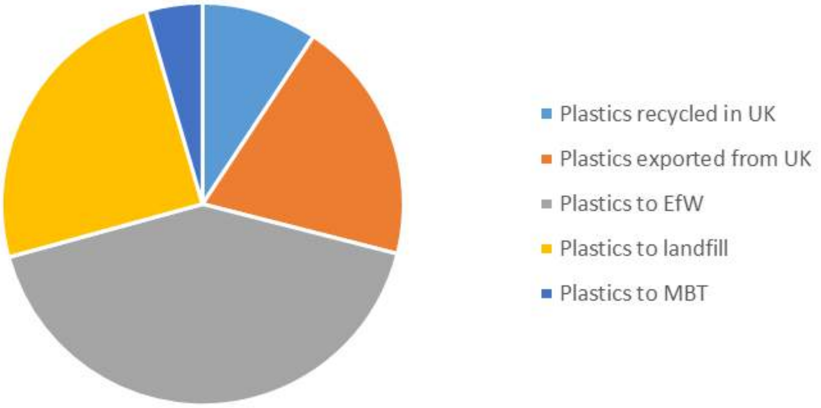

Figure 14 Fate of all waste plastic arisings in the UK, as proportion of total plastic arisings of 3.3 Mtonnes/annum (Wrap and Valpak, 2016)

Emissions due to diverting plastic from landfill or recycling

Schonfield (2008) carried out an in-depth LCA to compare a range of options for treatment of a mixed waste plastic stream sourced as an output from a materials recycling facility (MRF). The options examined included landfill, incineration with energy recovery, use as solid recovered fuel (SRF) in a cement kiln, two pyrolysis-type processes for production of oils, and a range of recycling processes. The study concluded that recycling had substantial GHG benefits compared to the other options, due to the avoided emissions from producing primary products. However, the assessment also showed that if a large proportion (estimated to be around 70%) of the material cannot be recycled to sufficient purity to replace virgin plastic, but can instead only substitute for wood or concrete, then some energy-recovery processes are preferential in terms of GHGs.

It is generally assumed that plastics in landfill do not contribute to GHG emissions as they do not degrade on an appreciable timescale. Under IPCC guidelines (2006)[68] plastic is counted as an 'inert' in solid waste disposal and no emissions from landfilling plastic are included within the inventories. The USA EPA Waste Reduction Model (WARM) also assumes that no degradation of plastics occurs in landfill.[69] Published LCA studies also generally make this assumption when carried out over a short to medium term time horizon. There are some fossil based synthetic polymers that can biodegrade[70], but doubt has been cast on whether those labelled compostable or degradable do in fact degrade effectively,[71] and they would likely require specific landfill conditions in order to do so.[72] Oxo-

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[68] IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas inventories, Volumne 5, Waste, Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html (Accessed on 29th November 2017)

[69] US EPA (2016) management practices chapters, Available from: https://www.epa.gov/warm/documentation-chapters-greenhouse-gas-emission-and-energy-factors-used-waste-reduction-model (Accessed on 28th September 2017)

[70] Leja, K., Lewandowicz, G. (2010) Polymer Biodegradation and Biodegradable Polymers – a Review, Polish J. of Environ. Stud. Vol. 19, No. 2, 255-266

[71] Adamcová, D., Vaverková, M. (2013) Degradation of Biodegradable/Degradable Plastics in Municipal Solid-Waste Landfill, Pol. J. Environ. Stud. Vol. 23, No. 4, 1071-1078

[72] Ishigaki, T., Sugano, W., Nakanishi, A., Tateda, M., Ike, M., Futita, M. (2004) The degradability of biodegradable plastics in aerobic and anaerobic waste landfill model reactors, Chemosphere. ;54(3):225-33, Available from: https://www.ncbi.nlm.nih.gov/pubmed/14575734

compostable plastics, which have had additives added to make them degrade faster, may degrade in aerobic conditions but are unlikely to biodegrade in the absence of air – the conditions found inside a landfill.[73] Therefore it can be assumed that the majority of waste fossil plastic in landfills does not degrade and sequesters all carbon.

Emissions due to diverting plastics from combustion

If the energy from combustion is not recovered and used for generation of electricity or heat then there are no indirect emissions associated with diverting that plastic towards liquid fuel production.

If useful heat or electricity was produced from combustion of the plastic, indirect emissions would occur associated with producing electricity or heat to replace that which would have been provided by the combustion of the waste plastic. The magnitude of these emissions depends on: the energy content of the plastic stream, the efficiency with which this is converted into electricity, and the emissions factor of the electricity or heat that is required to replace this.

- Individual plastics have very different energy values and the overall energy value of a waste plastic stream can be reduced by contamination, so there are a number of factors on which the energy value of a waste plastic stream depends. A recent study calculated that the LHV of a non-recycled mixed plastic stream in the USA was 35.7MJ/kg[74].
- The efficiency with which plastic is converted into electricity can vary substantially. In an LCA report for WRAP, Schonfield (2008)[75] assumes a conversion efficiency of 23% (LHV) as a baseline, and a high efficiency scenario with a conversion efficiency of 30%.

Waste plastic can also be combusted in cement kilns, but in this case it is challenging to estimate what fuel is used instead when this plastic is diverted to liquid fuel production. In some European countries up to 70% of the fuel used in cement plants is waste-derived, a portion of which is from waste plastic.[76] Cemex claim that 57% of their fuel usage is alternative fuel[77], while Hanson Heidelberg Cement group have used between 45% and 54% waste fuels annually since 2014. Waste plastic diverted towards liquid fuel production might therefore be replaced by either coal or other alternative fuels in cement kilns. A worst case scenario of 100% replacement by coal is modelled in Figure 15.

Indicative fuel chain calculations

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[73] THOMAS, N.L. ... et al., 2012. Oxo-degradable plastics: degradation, environmental impact and recycling. Proceedings of the Institution of Civil Engineers: Waste and Resource Management, 165 (3), pp. 133 - 140. Available from: https://dspace.lboro.ac.uk/dspace-jspui/bitstream/2134/13941/4/warm165-133.pdf

[74] Tsiamis, D.D., Castaldi, M.J. (2016) Determining Accurate Heating Values Of Non-Recycled Plastics (NRP), Available from: https://plastics.americanchemistry.com/Energy-Values-Non-Recycled-Plastics.pdf (Accessed on 29th September 2017)

[75] Schonfield, P (2008) LCA of management options for mixed waste plastics, for Wrap, ISBN: 1-84405-397-0, available from: http://bit.ly/2vRjb3D

[76] MPA (2015) Alternative fuels and raw materials in cement kilns: Cement quality and concrete performance, Available from: http://cement.mineralproducts.org/documents/FS_7_Alternative_fuels_and_raw_materials_in_cement_kilns.pdf

[77] Cemex (n.d.) Alternative fuels, Available from: http://www.cemex.co.uk/alternativefuels.aspx

Indicative GHG emissions of fuels produced from waste plastics are given in Figure 15, calculated using method A-2 and method B (see section 3.6.2). Several counterfactual feedstock use scenarios are considered, but diversion of plastic from recycling is not considered, as this is prevented from happening through the sustainability assessment framework.

Data on conversion efficiency (0.63MJ_{fuel}/$MJ_{plastic}$) and process emissions (6 gCO_2eq/MJ) was taken from Benavides (2017), which was itself based on a survey of five companies using pyrolysis to produce liquid transport fuels. Assumed efficiency of plastics conversion to electricity is 23%, and a current UK grid electricity emissions factor of 72.78 gCO_2eq./MJ[78].

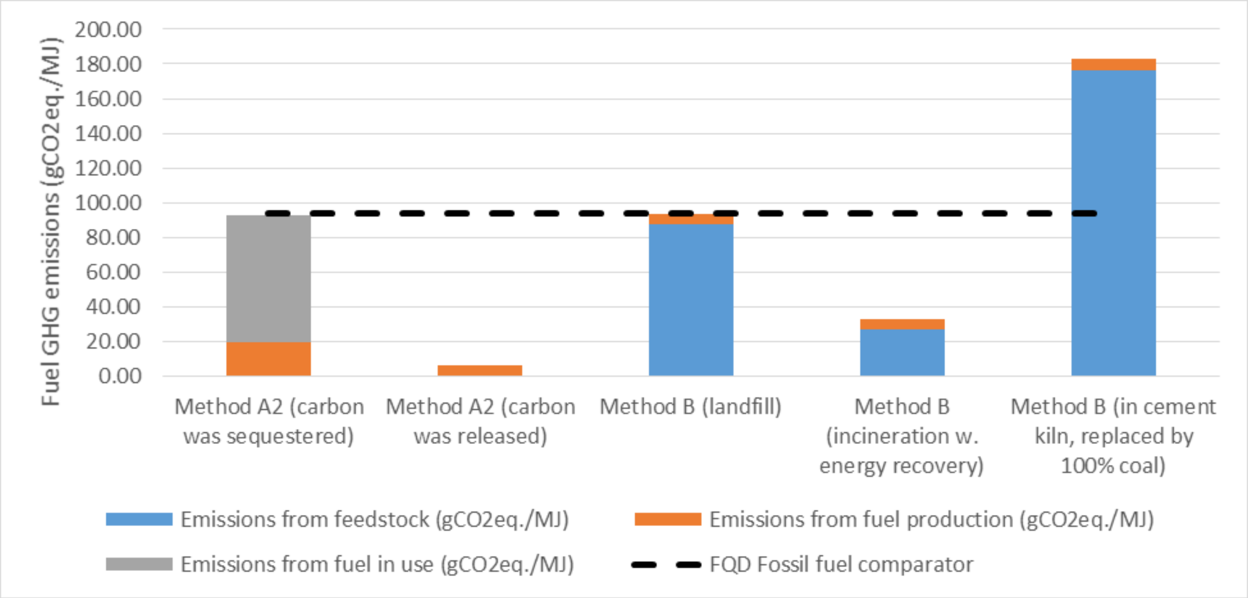

Figure 15 GHG emissions of fuels produced from waste plastic, using methodologies A2 and B, counterfactual feedstock use is given in brackets

Using method B, the GHG emissions of the fuel are very sensitive to assumptions around the resource that is used to replace the original utility of the plastic. Figure 16 demonstrates how, in the case of fuels produced from plastics diverted from EfW, the GHG emissions of the fuel vary with the emissions factor of the electricity that is required when plastic is diverted.

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[78] Calculated from figure given in National Grid Future Energy scenarios workbook for emissions factor of UK generation capacity - with 8% uplift for T&D losses to represent GHG emissions of electricity delivered to customer

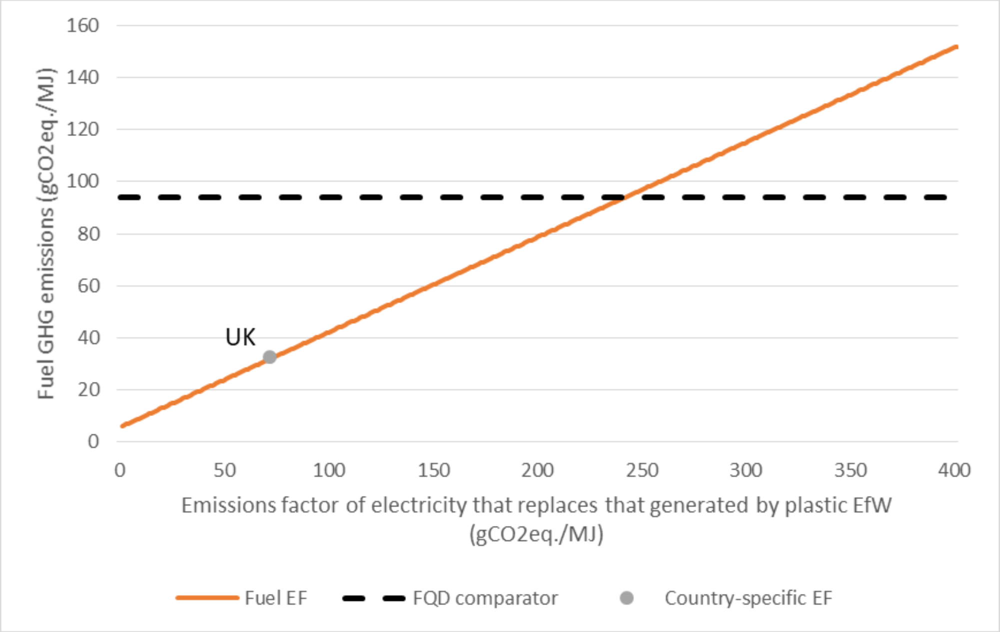

Figure 16 Emissions of fuel produced from waste plastic, where plastic diverted from EfW - sensitivity on grid electricity emissions factor

DfT should note that as countries' grid emissions factors change over time, the GHG emissions associated with a fuel which diverts feedstock from electricity production would also change over time. An assessment of the GHG emissions of a fuel at any given point in time should use the most up to date grid emissions factor at that time, whilst an assessment of the likely GHG emissions of a plant over its whole lifetime should account for anticipated changes in the carbon intensity of the grid over that period.

Fuel produced from waste tyres

Summary

The GHG emissions associated with using waste tyres as a feedstock depends on the use from which the tyres are being diverted:

- Diversion of tyres from landfill or re-use results in high GHG emissions associated with the feedstock.
- Tyres diverted from combustion with energy recovery can have GHG emissions ranging from low to high, depending on the energy that replaces the tyre.
- Tyres diverted from combustion without energy recovery would be likely to have low GHG emissions

Most waste tyres in the UK are either re-used or used for energy recovery, so fuels produced from waste tyres are moderately likely to increase GHG emissions compared to conventional gasoline or diesel.

Most likely fate of waste tyres in the UK

In the UK today the majority of waste tyres are recycled, used for energy recovery, or exported for re-use or energy recovery (Figure 12).

Diversion of tyres from landfill or re-use

Whilst used tyres can be re-treaded, re-used or recycled, the sustainability assessment framework ensure that tyres should not be diverted from these fates to make liquid transport fuels, so this scenario will not be further considered here.

If tyres are landfilled the carbon is sequestered, as tyres do not degrade. Therefore as for the waste fossil plastic stream, the GHG emissions from fuels produced from tyres that would have been landfilled is likely to be similar to the GHG emissions from conventional gasoline or diesel.

Diversion of tyres from combustion:

If tyres are diverted from combustion without energy recovery then the GHG emissions associated with use of those tyres for liquid fuel production are low.

If tyres are diverted from combustion with energy recovery then, as outlined above for waste plastics, GHG emissions could range from low to high depending on what type of energy is used to replace the energy that was generated by tyre combustion.

As for waste plastics, waste tyres can be combusted in cement kilns. A worst case scenario of 100% replacement with coal would produce a fuel with GHG emissions substantially higher than conventional gasoline or diesel.

Fuel produced from mixed waste streams

Summary:

The GHG emissions associated with using the fossil fraction of mixed waste (municipal solid waste or commercial and industrial waste) as a feedstock depends from which use the waste is diverted:

- Diversion of mixed waste from landfill results in high GHG emissions associated with the feedstock.
- Mixed waste diverted from combustion with energy recovery can have GHG emissions ranging from low to high, depending on the fuel that replaces it.
- Mixed waste diverted from combustion without energy recovery would be likely to have low GHG emissions

Use of mixed waste for liquid fuels production is likely to divert it either from landfill or from combustion with energy recovery in the UK.

Most likely fate of mixed waste in the UK

Figure 17 illustrates that the majority of local-authority collected waste in England is recycled or composted, the second most prevalent treatment route is incineration with energy from waste, and around 20% is still sent to landfill.

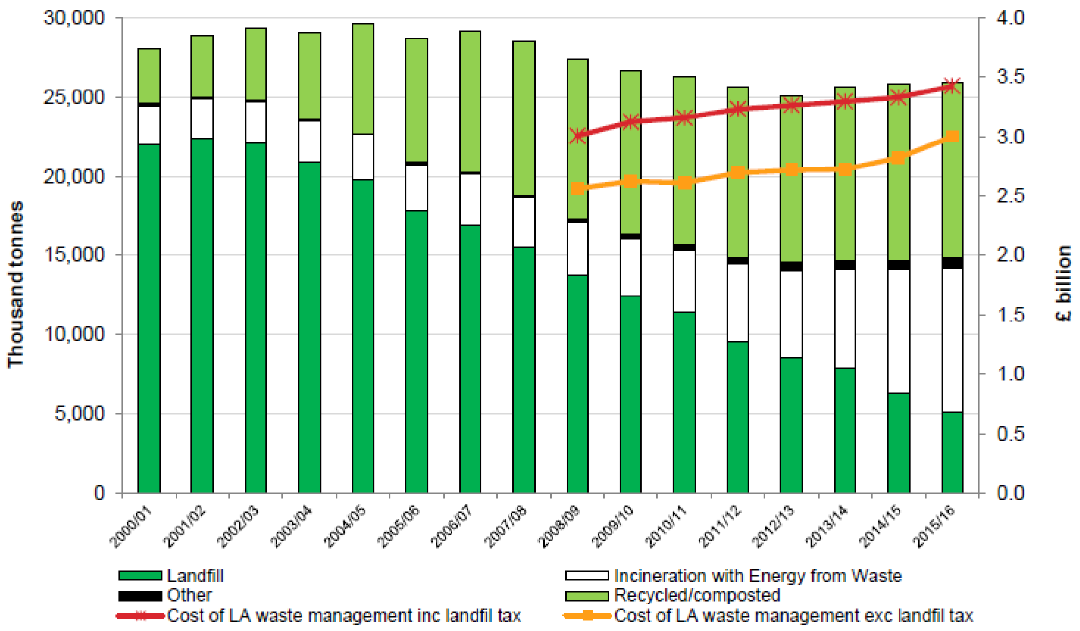

Figure 17 Management of local authority collected waste in England from 2000 to 2015[79]

The sustainability assessment framework aims to ensure that material that could have been recycled is not diverted towards liquid fuel production. Therefore the most likely scenario is that mixed waste used for liquid fuel production is diverted from landfill or energy from waste.

Landfill:

When the fossil portion of mixed waste is diverted from landfill for fuel production, additional emissions are released into the atmosphere according to how much of that waste would have been sequestered in landfill. As noted above, in both the IPCC[80] and US waste emission models[81], the non-biogenic portion of landfilled waste is generally assumed not to degrade.

Combustion:

When the fossil portion of mixed waste is diverted from combustion with production of heat and/or power, GHG emissions are caused by the alternative energy that is require to produce that electricity or heat. The magnitude of these emissions depends on: the energy content of the waste stream, the efficiency with which this is converted into electricity and heat, and the emissions factor of the electricity or heat that is required to replace this.

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[79] DEFRA (2017) Digest of Waste and Resource Statistics 2017 edition, Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/607416/Digest_of_Waste_and_Resource_Statistics__2017_rev.pdf (Accessed on 23rd October 2017)

[80] IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas inventories, Volumne 5, Waste, Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html (Accessed on 29th November 2017)

[81] US EPA (2016) management practices chapters, Available from: https://www.epa.gov/warm/documentation-chapters-greenhouse-gas-emission-and-energy-factors-used-waste-reduction-model (Accessed on 28th September 2017)

- The energy content of the fossil fraction of mixed waste would vary according to the waste composition. Analysis of a typical UK mixed waste stream[82] indicated that the fossil portion has a LHV of 13.3 MJ/kg, although this can vary substantially.
- A 2013 review of 25 operational EfW plants in the UK[83] revealed that only 3 out of 25 plants were at the time exporting heat, and even these were not maximising their heat export capacity. Of the four case-study plants, net electrical efficiency ranged from 21% to 24%.

As for plastics the GHG emissions of the fuel are very sensitive to the emissions factor of the energy source that replaces that which was generated from waste.

Indicative fuel chain calculations

Indicative GHG emissions of fuel produced from the fossil portion of mixed waste are given in Figure 18 calculated using method A-2 and method B. Several counterfactual feedstock use scenarios are considered, but diversion of wastes from recycling is not considered, as this is prevented from happening through the sustainability assessment framework.

The processing emissions are assumed to be 10 $gCO_2eq./MJ$, based on a range of values reported in the literature for the production of hydrocarbon diesel/jet fuel from MSW by gasification and Fischer-Tropsch synthesis. It should be emphasised that these process emissions are indicative only, as they depend completely on the production process in question, and can vary substantially. For example figures in Suresh (2016)[84] range from 39.21 $gCO_2eq./MJ$ for jet fuel produced from Fischer-Tropsch gasification of MSW, to 90.76 $gCO_2eq./MJ$ for jet fuel produced via an alcohol-to-jet process.

Due to the variable nature of mixed fossil waste streams and limited data on conversion of waste to fuel, there is a high level of uncertainty in these results, and they aim to be indicative but not representative of one particular process.

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[82] DEFRA (2014) Carbon recovery for residual waste, A carbon based modelling approach, Available from: http://randd.defra.gov.uk/Document.aspx?Document=11918_WR1910Energyrecoveryforresidualwaste-Acarbonbasedmodellingapporach.pdf

[83] Nixon, J.D., Wright, D.G., Dey, P.K., Ghosh, SkK., Davies, P.A. (2013) A comparative assessment of waste incinerators in the UK, *Waste management*, 33 11) 2234-2244, Available from: http://www.sciencedirect.com/science/article/pii/S0956053X13003723?via=ihub

[84] Suresh (2016) Environmental and economic assessment of transportation fuels from municipal solid waste, Available from: http://lae.mit.edu/uploads/LAE_report_series/2016/LAE-2016-002-T.pdf (Accessed on 5th December 2017)

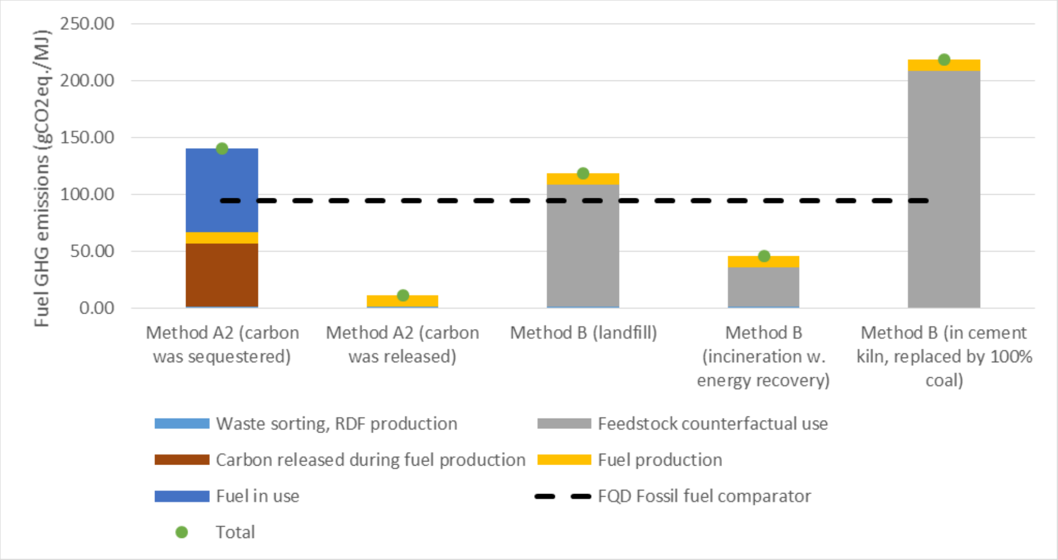

Figure 18 GHG emissions of fuels produced from MSW, using methodologies A2 and B, counterfactual feedstock use is given in brackets

Fuel produced from waste fossil liquids

Summary

Waste fossil liquids produced in the UK and Europe are likely to be either disposed of through incineration, particularly if they are hazardous, or transformed into secondary liquid fuel (SLF) which is produced by waste management companies such as Veolia and Chemkel in the UK and can be used in cement kilns.[85] Use of waste fossil liquids for liquid transport fuel production could cause no indirect emissions if the feedstock would have been incinerated with no energy recovery, or could have indirect emissions ranging from low to high if the feedstock would have been used to generate energy, therefore it is assessed in Table 6 as moderately likely to cause increased GHG emissions compared to conventional gasoline or diesel.

Combustion:

If the counterfactual is incineration with no energy recovery, there are no indirect emissions associated with diverting the waste fossil liquids away from this fate.

If the liquids would have otherwise been used to provide heat and/or power then there are GHG emissions associated with alternative methods of producing this energy. If secondary liquid fuels are diverted away from use in lime and cement kilns, they may be replaced by fossil fuels, or they may be replaced by other waste-based fuels which are also commonly used in these industries in the UK, including waste tyres. As noted above, Cemex claim to use 57% alternative fuels in their cement kilns, including SLF and waste tyres.[86] Therefore the indirect emissions associated with using this feedstock for transport fuel production could range from low to high depending on the energy with which it is replaced.

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[85] Environment Agency (2008) The use of substitute fuels in the UK cement and lime industries, Available from: http://cdn.environment-agency.gov.uk/scho1207bnna-e-e.pdf (Accessed on 26th September 2017)

[86] Cemex (2017) Alternative fuels, available from: http://www.cemex.co.uk/alternativefuels.aspx (Accessed on 26th September 2017)

Landfill:

In the UK it is not permitted to dispose of liquid waste in landfill,[87] however this could be a possible counterfactual if the feedstock originates in another country, where disposal of hazardous liquids in landfill is permitted. If liquid fossil waste feedstock was supplied into the UK from regions where landfill disposal was an option, further work would be required to understand the impact of diverting it from this use.

Fuel produced from industrial waste CO-containing gases

Likely fate of waste CO-containing gases

Waste gases are extremely expensive to store, and cannot be released to the atmosphere as CO, therefore are combusted either without energy recovery (flared) or with energy recovery in the form of electricity and/or heat.

Indicative fuel chain calculations

Indicative GHG emissions values are given for fuels produced from industrial waste CO-containing gases in Figure 19. Calculation of GHG emissions using option A-2 (system boundary at point of collection of feedstock) is only considered for these fuels in the case where this carbon was released, because there is no way to store or sequester the carbon in the gaseous feedstock. It is always released to the atmosphere either by flaring or combustion for energy recovery.

Two illustrative counterfactuals are used with method B:

- Gas would have been incinerated for energy recovery, additional electricity with UK grid electricity emissions factor required to replace this.
- Gas would have been flared, with no energy recovery

These calculations indicate that these fuels are unlikely to increase GHG emissions compared to conventional diesel or gasoline, therefore in Table 6 they are rated as low likelihood that this risk will materialise.

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[87] Environment Agency (2010) Waste acceptance at landfills, Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/296422/geho1110btew-e-e.pdf (Accessed on 26th September 2017)

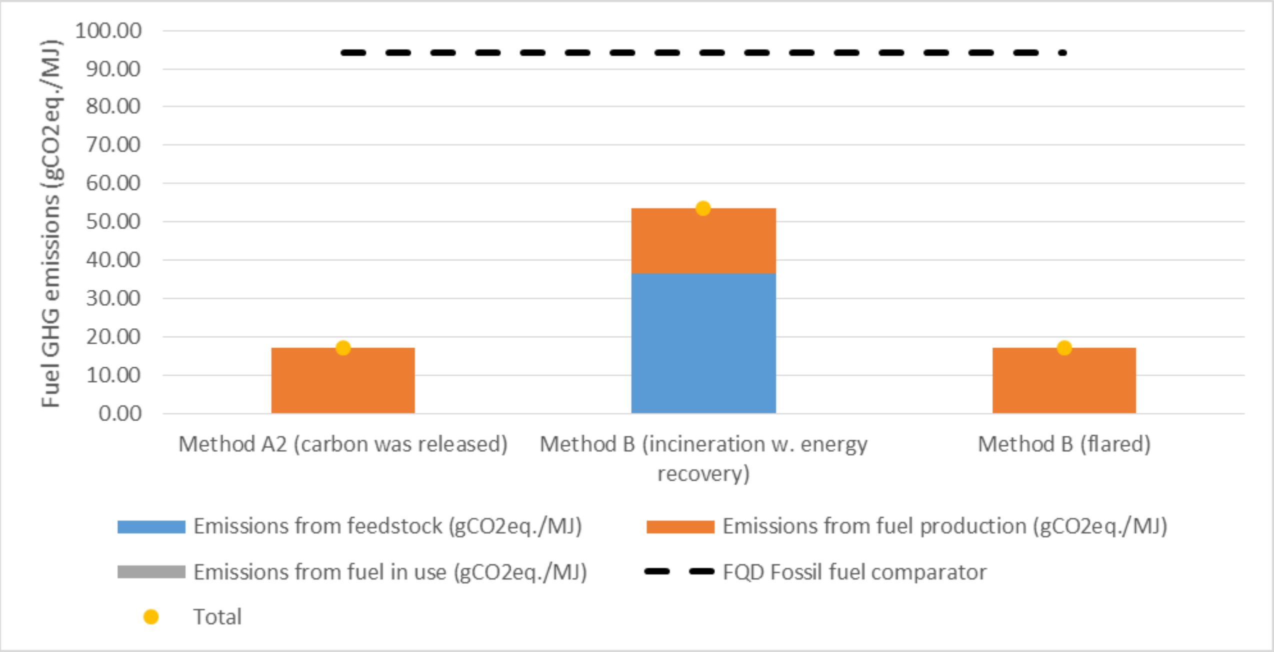

Figure 19 GHG emissions of fuel produced from industrial CO gases using methodologies A2 and B, counterfactual feedstock use is given in brackets

Fuel produced from CO_2

Question 2b of the sustainability assessment framework rules out the production of fuels from CO_2 when that CO_2 is not a waste. Therefore the CO_2 used to produce 'RFNBO-type' fuels must have been captured either from the atmosphere or from a waste stream that would have entered the atmosphere. The energy used to produce LCFF fuels from CO_2 must be fossil-based energy, as use of renewable energy would result in a RFNBO.

Based on the methodology proposed for LCFFs which have no energy content in their feedstock, two main factors will impact the overall GHG emissions of fuels made from CO_2:

- The GHG impact of capturing the CO_2. This varies depending on the source of the CO_2. For example a relatively pure concentrated CO_2 stream from an industrial process is likely to require significantly less energy (and hence less GHG impact) than capturing CO_2 from the air.
- The GHG intensity of the energy used in the production process. Use of low-carbon energy (e.g. nuclear electricity) could give low GHG emissions of fuel produced from CO_2, but most fossil energy sources have higher GHG emissions.

Therefore fuels produced from CO_2 are assessed in Table 6 as having moderate likelihood of increasing GHG emissions compared to conventional gasoline or diesel.

Hydrogen

Hydrogen produced from natural gas is considered under the subheading 'Fuel produced from natural gas'

Hydrogen produced from electricity, and CO_2 or water should be assessed following the methodology laid out in section 3.6.2.1 which is equivalent to the methodology for RFNBOs currently under consultation by DfT. As discussed above, hydrogen produced from UK grid electricity must, under these proposals use an average emissions factor from the UK grid. We also give indicative emissions for hydrogen produced solely from natural gas and nuclear electricity, which would be the emissions factors if the renewable and non-renewable portions of these fuels could be given different GHG emissions.

Indicative fuel chain calculations

Figure 13 illustrates the emissions of hydrogen produced from natural gas by steam methane reforming (orange bars) and by electrolysis (blue bars), assessed according to the appropriate methodologies. Electrolysis efficiency of $70MJ_{hydrogen}/MJ_{electricity}$ is assumed, and data for hydrogen production from natural gas is taken from the JEC Well-to-Wheels study, which uses this method.

For all hydrogen emissions factors shown in Figure 20, it is assumed that the fuel is used in a fuel cell vehicle, so a multiplier of 0.4 has been applied to reflect higher powertrain efficiency than an internal combustion engine.

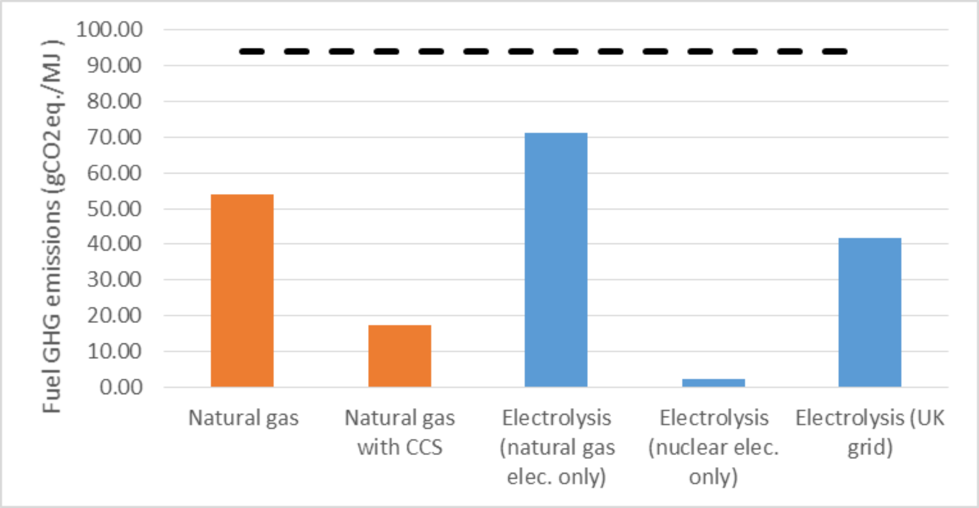

Figure 20 GHG emissions of hydrogen produced from non-waste fossil fuel (orange bars) and electricity (blue bars). Dashed line shows FQD fossil fuel comparator (94.1gCO_2eq./MJ)

The GHG emissions for production of hydrogen from electricity are assessed based on the RFNBO methodology laid out in the most recent RTFO consultation (Figure 20, blue bars). As discussed above, hydrogen produced from UK grid electricity must, under these proposals, use an average emissions factor from the UK grid. We also illustrate the emissions factor of hydrogen produced solely from natural gas and nuclear electricity.