Waste to products – Technology and economic assessment (phase 1)

WASTE TO PRODUCTS – TECHNOLOGY AND ECONOMIC ASSESSMENT (PHASE 1)

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EXECUTIVE SUMMARY

The EMG and Soil Wastes and Groundwater group (SWG) of the EI and Concawe have commissioned E4tech to conduct a technical analysis of waste-to-products (WTP) technologies that could be integrated within the European refining system in the 2030 and 2050 timeframe. This study builds upon the findings of the Concawe 2050 study, but considers a different set of feedstocks, namely wastes. It explores specific types of wastes and looks at what could be the most attractive use of them considering pathways within (Phase 1) and outside (Phase 2) the refining sector. More specifically, this project considers which technologies could be integrated into the refining supply chain in order to process the wastes in scope (Phase 1) and what the alternative/ competing uses of these wastes could be outside the refinery supply chain (Phase 2). Phase 1 has just been concluded, with the main findings provided in this section.

Four waste-to-fuel (WTF) pathways were selected for more detailed examination, being focused on non-agricultural/forestry residues:

- Mixed plastic waste > pyrolysis to pyrolysis oil > refining
- Sewage sludge > hydrothermal liquefaction (HTL) to HTL oil > refining
- Mixed residual waste (MRW) > gasification to Fischer-Tropsch (FT)-wax > refining
- Municipal biowaste (including food and garden waste) > anaerobic digestion (AD) to biogas, to bioCH4, to FT-wax > refining

A literature survey was carried out to investigate the technology and supply chain, economics and financing, policy and regulatory, and sustainability aspects of these four WTF pathways.

The objective of Phase 1 is to initiate a deep dive into the selected WTF routes, and highlight some areas for further research. The initial set of conclusions are summarised here:

- When considering its position in the waste hierarchy relative to recycling, the use of these feedstocks for fuels may not be initially seen as favourable as using these feedstocks for forms of recycling, such as mechanical and chemical. However, it should also be noted that not all wastes can be recycled, and that chemical recycling technologies have also not yet reached commercial scale. This could offer an opportunity for using the non-recyclable parts of these materials to produce alternative fuels, replacing conventional oil-based ones.
- When using a consequential life cycle assessment (LCA) approach, diverting certain non-recyclable waste feedstocks away from energy from waste (EfW) plants and towards fuel production can result in greenhouse gas (GHG) savings. This shows there is opportunity for the WTF pathways to deliver GHG reductions compared to their current end-of-life (EoL) fates.
- From a technology and supply chain perspective, these pathways may enable refinery assets to be utilised, and enable the transition towards the use of lower carbon feedstocks. However, given the relatively small volume of these wastes in comparison with the scale of refineries, whilst these pathways may enable some degree of GHG reduction, other complementary feedstocks (e.g. e-fuels) or technologies (e.g. carbon capture and storage (CCS)) may be needed for fuels to reach net zero emissions on a well-to-wheel basis depending on the future demand scenarios considered.

Even though this study has provided a solid foundation to better understand how these WTF pathways may play a role in the energy transition within the refining context, it was also evident that key knowledge gaps remain, and need to be addressed in order to better understand what opportunities may exist for these pathways:

- Waste volumes and accessibility: detailed information on waste volumes, particularly regional data, is not readily available. A more detailed insight into the waste supply chain and how these can be accessed is needed.
- Technology and supply chain: a high degree of uncertainty exists in terms of the impact on refinery operations and final product quality if intermediate products processed at high levels (e.g. 10–30 % of refinery process feed), particularly for the waste plastic pyrolysis and sewage sludge pathways. More work is needed to understand whether it makes sense to transport wastes to larger, centralised primary conversion plants, or whether smaller, distributed primary conversion plants are more economically attractive for the WTF pathways considered.
- Economics and financing: feedstock costs, policy and gate fees for these wastes are geographically dependent and more work is needed to better understand how these could affect the viability of these pathways in different regions. Information on how certain process parameters impact the capital costs of certain technologies (e.g. gasifiers) is limited.
- Policy, regulatory and sustainability: for feedstocks which are fossil wastes, or are partly fossil-derived, there is not yet clarity on a universally agreed GHG calculation methodology. In particular, this has not yet been defined in the Renewable Energy Directive (REDII), leading to uncertainty around the possible level of policy support for pathways using these feedstocks. In addition, the Fuel EU Maritime Initiative and the EU Sustainable Aviation Fuel (SAF) mandate are yet to be defined.

1 INTRODUCTION

1.1 INTRODUCTION AND CONTEXT

The EMG and SWG of the EI and the Refining into Energy Transition Management Group (RET MG) of Concawe have commissioned E4tech to conduct a technical analysis of WTP technologies that could be integrated within the European refining system in the 2030 and 2050 timeframe. The study builds on the assessment conducted in the Concawe Refinery 2050 study.

The proposed study is split into the three phases outlined as follows. The overall aim of the study (Phases 1–3) is to produce a technical publication with the working title of *Waste to products – technology and economic assessment*. This publication would build on the analysis and methodology in the Concawe Refinery 2050 report to analyse how waste feedstocks (not considered in detail in the Concawe Refinery 2050 document) could be integrated within the European refining system in 2030 and 2050. The feedstocks within scope of this work, as agreed with the EI Steering Committee and Concawe, are detailed in 2.1.

A focus of the Concawe Refinery 2050 study was to consider how certain feedstocks (forestry and agricultural residues, used cooking oil and carbon dioxide (CO_2)) could be integrated in the existing refinery supply chain and asset base to meet 2050 demand for road fuels and petrochemicals in the EU. The study described in this report goes beyond the feedstocks previously analysed there, explores specific type of wastes, and takes a different perspective looking at what could be the most attractive use of them considering pathways within (Phase 1) and outside (Phase 2) the refining sector. More specifically, this project will consider which technologies could be integrated into the refining supply chain in order to process the wastes in scope (Phase 1) and what the alternative/competing use of these wastes could be outside the refinery supply chain (Phase 2). For the latter (Phase 2), these could include, but are not limited to, incineration with/without energy recovery, AD, mechanical recycling of plastic waste, chemical recycling of plastic waste that does not produce refinery feeds (e.g. chemolysis).

Phase 2 will also explore potential future availability of wastes with a focus on how to encourage waste minimisation while maximising the transformation of the residual waste into valuable products, and potential implications for the EU refining system. It is expected to include how the refinery WTP pathways, and the alternatives, fit within the waste hierarchy and will consider related EU policy.

Phase 3 would then develop a research summary to be used by a range of stakeholders, based on the findings from Phases 1–2. The research summary would cover the technical, economic, and environmental viability of WTP pathways until 2050 under specific scenarios and include case study examples.

1.2 FOCUS OF THIS REPORT AND STUDY SCOPE

This report only covers Phase 1 of the broader study as outlined in 1.1. Whilst refineries make chemical feedstocks such as naphtha, and products such as propylene, the majority of refinery products are fuels, hence the decision to use the term WTF.

In Phase 1, the work was divided into two Tasks, which reflect the structure of this report:

Task 1 – Selection of WTF refinery pathways	**Task 2 – WTF refinery pathways literature review**
– Provide an overview of key waste streams to be considered for this study – Describe how four WTF pathways were selected for more detailed study in Task 2	– Conduct a literature review to assess the current state of knowledge of the WTF pathways and identify knowledge gaps, considering technical and supply chain, economic and financial, policy and regulatory, and sustainability aspects

The report concludes with a section that highlights the key findings, as well as the knowledge gaps and recommendations for future work.

It is important to note that this work did not involve any primary research; all information presented in this report has come from a literature review and E4tech's in-house expertise. Additionally, this is not meant to be a comprehensive literature survey; the aim is to cover the key literature on the most pertinent issues relating to this topic.

2 SELECTION OF WTF REFINERY PATHWAYS (TASK 1)

In this study, a pathway consists of a feedstock, a primary conversion technology and refinery conversion technologies. This section describes the rationale for the selection of the pathways studied in this project and presents the data relating to the volumes of waste available and their current EoL fates.

2.1 FEEDSTOCKS SHORTLISTED FOR THE STUDY

This subsection describes the feedstocks considered for the study, their current EU volumes, and current EoL fates.

Table 1 gives an overview of the seven types of waste that were proposed as feedstocks for this study, their current indicative EU volumes and the amounts directed to different EoL fates in the EU. These seven feedstocks were selected for consideration based on volumes available in the EU, and whether there has been interest (in either industry or academia) in terms of using these wastes for fuel production. Four of these seven feedstocks were subsequently selected to form part of the four pathways studied in greater depth in section 3.

Table 1: Overview of the waste volumes and current EoL fates for seven shortlisted feedstocks

	EU volumes Mt/a	**Current EoL fate**	**Source**
Mixed residual waste	~222	Landfill (37 %), EfW (40 %), incineration (4 %), recycling and backfilling (19 %)	(Eurostat, *Treatment of waste by waste category, hazardousness and waste management options*)
Non-recyclable mixed plastic waste (materials recovery facility (MRF) and mechanical recycling residues)	~10	Landfill (37 %), EfW (63 %)	(Eurostat, *Treatment of waste by waste category, hazardousness and waste management options*)
Municipal biowaste (including food and garden waste)	~48	Composting (64 %), AD (26 %), combined composting and AD (10 %)	(UK Environmental Change Network *Compost production in Europe*)

Table 1: Overview of the waste volumes and current EoL fates for seven shortlisted feedstocks (continued)

	EU volumes Mt/a	Current EoL fate	Source
Landscape care biomass	Currently unknown	Unused, composting, EfW, landfill	N/A
Sewage sludge	~11	Landfill (8 %), land treatment/ release into water (6 %), EfW (17 %), incineration (11 %), land application for agriculture or ecological improvement (58 %)	(Eurostat, *Treatment of waste by waste category, hazardousness and waste management options*)
Used tyres	~3	Recycling (~62 %), cement kilns (~32 %), EfW (~6 %)	(European Tyre and Rubber Manufacturers Association (ETRMA), *Europe – 92 % of all end of life tyres collected and treated in 2017*)
Automotive shredder residue (ASR)	~3	Landfill (mostly), EfW	(ARN Recycling BV, *Aim to realise 95 % ELV-recycling in the Netherlands by means of post shredder technology*)

Waste feedstock definitions

Mixed residual waste: refers to the waste collected from private households which is not separated for reuse, recycling, or composting. This waste stream accounts for a large proportion (~20 %) of EU waste, with the majority being directed to landfill or EfW plants.

Non-recyclable mixed plastic: waste includes plastic waste that is not separated and sorted for recycling at MRFs. For the mixed plastic waste that is collected for recycling, 20–30 % of residues are generated during the mechanical recycling process. The residues generated during mechanical recycling are also included in this waste volume, which leaves around ~10 Mt of mixed plastic waste that is not recycled.

Municipal biowaste (including food and garden waste): corresponds to biowaste that is collected separately as opposed to the biowaste fraction which is present in MRW (*Compost production in Europe*). The composition of biowaste is mainly food and garden waste that can be collected separately or as a mixture. The EoL fate of municipal biowaste is directed towards AD and composting, which are both waste management options that are higher up the waste hierarchy than recovery.

Landscape care biomass: is defined as primary woody and grassy residues from maintenance of urban green areas, roadsides, waterways, hedgerows, etc. A significant (but undefined) quantity is left unused. When collected, it is typically used for composting purposes, local firewood, or disposed of as waste.

Sewage sludge: refers to common sludges which can be defined as: sludges from treatment of public sewerage water; biodegradable sludges from treatment of other wastewater; sludges from purification of drinking and process water; unpolluted dredging spoils, and septic tank sludge and waste from sewage cleaning (Commission Regulation (EU) No 849/2010 of 27 September 2010 amending Regulation (EC) No 2150/2002 of the European Parliament and of the Council on waste statistics). Most of the sewage sludge is directed to land application for agriculture or ecological improvement, which is classed as recycling. The remaining waste is sent for energy recovery, incineration or to landfill, which is similar to the current EoL fate of most of the MRW.

The **used tyres** waste stream describes the EoL management of tyres at the end of their useful life in the European tyre industry. Recycling covers: granulation; incorporation into cement; application in steel mills and foundries; reuse for other purposes; pyrolysis, and civil engineering applications. Energy recovery was split into cement kilns and EfW plants (ETRMA *Europe – 92 % of all end of life tyres collected and treated in 2017*).

ASR is defined as the residue that remains following vehicle dismantling into parts and shredding. The majority of ASR is currently landfilled, with some going to energy recovery (*Aim to realise 95 % ELV-recycling in the Netherlands by means of post shredder technology*).

2.2 PRIMARY CONVERSION TECHNOLOGIES CONSIDERED FOR THE STUDY

Based on research and development, and current level of interest, four primary conversion technologies were proposed to be part of this study, as outlined in Table 2.

Table 2: Primary conversion technologies in scope

Primary conversion(s)	Primary products
Pyrolysis	Pyrolysis oil
HTL	HTL bio crude
Gasification and FT	FT wax
AD to biogas, upgrade to bioCH4 and reforming to syngas, and FT	FT wax

These primary conversion technologies are described in detail in 3.1.

2.3 SELECTION OF FEEDSTOCK – PRIMARY CONVERSION TECHNOLOGY COMBINATIONS

Using the feedstocks outlined in 2.1, and the primary conversion technologies in 2.2, three key criteria were used to aid the selection of the four feedstock – primary conversion technology combinations considered:

- Fit with the waste hierarchy: whether using the feedstocks for fuel production would be a better use in comparison with their current EoL fates. Further details on the waste hierarchy can be found in 3.4.1.
- Projected volumes of waste available: larger volumes considered to be more attractive.
- Feedstock fit with primary conversion technologies.

Table 3: Summary of the criteria used to select the four WTF pathways

	EU volumes per year*	**Current EoL fate**	**Fit with primary conversion technologies**
Mixed residual waste	~222	Landfill (37 %), EfW (40 %), incineration (4 %), recycling and backfilling (19 %)	Gasification+FT
Non-recyclable mixed plastic waste (MRF and mechanical recycling residues)	~10	Landfill (37 %), EfW (63 %)	Pyrolysis, HTL, Gasification+FT
Municipal biowaste (incl. food and garden waste)	~48	Composting (64 %), AD (26 %), combined composting and AD (10 %)	AD+Reforming+FT, Pyrolysis, HTL, Gasification+FT
Landscape care biomass	Currently unknown	Unused, composting, EfW, landfill	Pyrolysis, HTL, Gasification+FT
Sewage sludge	~11	Landfill (8 %), land treatment/ release into water (6 %), EfW (17 %), incineration (11 %), land application for agriculture or ecological improvement (58 %)	HTL
Used tyres	~3	Material recovery (~62 %), cement kilns (~32 %), EfW (~6 %)	Pyrolysis, HTL, Gasification+FT
ASR	~3	Landfill (mostly), EfW	Gasification+FT

Acknowledging that there is a maximum of one feedstock per pathway within the scope of this work, the following four feedstock – primary conversion combinations were selected to form the four pathways to be studied in section 3. Note that these are not the only possible combinations, and that further work (beyond the study scope) could be carried out to assess the viability of other combinations as per Table 3. The four pathways are:

- MRW was selected due to it being the feedstock with the largest volume, and because currently it is mainly being used for purposes lower down the waste hierarchy than fuels, such as landfill. Gasification is acknowledged as being the most suitable primary conversion technology to use this feedstock, given that it is considered in general to be less sensitive to contaminants in the waste stream than the other technologies in the study. Furthermore, this pathway is already being developed by a number of low carbon fuel producers (see 3.2).
- Mixed plastic waste was selected because currently it is mainly being used for purposes lower down the waste hierarchy than fuels (landfill, EfW). Pyrolysis was selected as the most suitable primary conversion technology, given that this feedstock has been attracting increased interest from a number of low carbon fuel and chemical recycling developers who have built demonstration plants utilising pyrolysis technology.
- Sewage sludge was selected given that some of this material is currently used for purposes lower down the waste hierarchy (e.g. EfW) and there have been some concerns about its use for land application. HTL was selected as the most suitable primary conversion technology given its ability to handle feedstocks with large amounts of moisture and because it has already been studied as a possible way to convert sewage sludge to fuels.
- Municipal biowaste (including food and garden waste) was selected primarily owing to its availability in potentially large volumes. Even though significant amounts are already being used for purposes relatively high up the waste hierarchy (e.g. composting), using it as a fuel for hard to decarbonise sectors (e.g. aviation fuel) could be an option worthy of further study. Given the large amounts of moisture in the feedstock, and that it has already been proven as a suitable feedstock for AD, AD was chosen as the most suitable primary conversion technology.

Given that this study was limited to a maximum of four pathways, with a maximum of one feedstock per pathway, three feedstocks were not selected, with the rationale given here. It should be noted that this does not mean that these feedstocks (or others) would not be suitable feedstocks for the feedstock – primary conversion combinations described, as there may be reasons to examine these feedstocks as part of work beyond the scope of this study.

- Landscape care biomass was not selected for further study owing to uncertainty over the volumes of this waste that could be available, and because from a feedstock composition perspective, it was deemed as being quite similar to municipal biowaste which includes food and garden waste.
- ASR was not selected due to its relatively low volumes, and uncertainty over what types of pre-treatments might be needed to make it a viable feedstock for gasification. However, it should be noted that currently this feedstock is being used for purposes low down in the waste hierarchy (landfill, EfW).
- 'Used tyres' was not selected primarily because it is currently used for purposes higher up the waste hierarchy (material recovery). Furthermore, the volumes available are projected to be relatively small. There has been interest in the production of fuels from used tyres, particularly in the UK where the renewable fraction (not the fossil component) of used tyres is eligible for policy support (double counted under the Renewable Transport Fuel Obligation (RTFO)).

2.4 WTF PATHWAYS SELECTED

Using the four feedstock-primary conversion combinations noted in 2.3, a mapping of the possible refining pathways (and resultant products) was carried out, and is summarised in Table 4.

Table 4: Pathway mapping

Waste resource	Primary conversion (1)	Primary product	Refinery conversion	Main finished products (2)
Mixed plastic waste	Pyrolysis (with fractionation)	Fractionated products	Directly to blending	Diesel; gasoline; fuel oil
			To hydrotreatment	Diesel; gasoline; fuel oil
	Pyrolysis (without fractionation)	Syncrude	To crude distillation unit (CDU)	Diesel; jet; gasoline; other products
			To fluid catalytic cracking (FCC)	Gasoline; C3/C4 olefins (fuel-oil; coke; gas)
			To hydrocracking (HCK)	Diesel; jet; gasoline
Sewage sludge	HTL with upgrading	Fractionated products	Directly to blending	Diesel; gasoline; fuel oil
	HTL (without upgrading)	HTL oil	To hydrotreatment	Diesel (naphtha; fuel-oil)
			To FCC	Gasoline (fuel-oil; coke; gas)
			To HCK	Diesel; jet; gasoline
Mixed residual waste	Gasification + FT synthesis + hydrocracking	Fractionated products	Directly to blending	Diesel; jet; gasoline; lubricating oil; wax
	Gasification + FT synthesis	FT syncrude	To CDU	Diesel; jet; gasoline; other products[1]
			To FCC	Gasoline; C3/C4 olefins (fuel-oil; coke; gas)
			To HCK	Diesel; jet; gasoline
Municipal biowaste (including food and garden waste)	AD + steam reforming + FT synthesis + HCK	Fractionated products	Directly to blending	Diesel; jet; gasoline; lubricating oil; wax
	AD + steam reforming + FT synthesis	FT syncrude	To CDU	Diesel; jet; gasoline; other products
			To FCC	Gasoline; C3/C4 olefins (fuel-oil; coke; gas)
			To HCK	Diesel; jet; gasoline

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[1] 'Other products' includes chemical naphtha, heating oil, marine fuel, lubricants

In order to keep the study relatively focused, it was not possible to explore all the refining pathways highlighted in Table 4. The following factors were used to focus the study on a more narrowly defined set of four pathways:

- This report focuses on WTF upgrading in the refinery rather at the primary conversion facility in order to identify synergies and barriers associated with utilising existing refining infrastructure. This meant that the refining pathways wherein the primary product is a 'fractionated' product (i.e. where product upgrading takes place at the primary conversion step rather than the refinery) were not considered in detail in this study.
- Gasoline demand is expected to decline faster than other products. Therefore, this report focuses on pathways which are oriented to distillates (diesel and jet), but still considers other pathways to produce other fuels such as gasoline.

As a result, the four precisely defined pathways to be examined in more detail in Task 2, are shown in Table 5. It should be noted that these four pathways are intended as illustrative examples of potentially viable fuel production pathways and are not meant to indicate which could be the most optimal pathways for fuel production from these feedstocks.

Table 5: Selected pathways

Waste resource	**Primary conversion (1)**	**Primary product**	**Refinery conversion**	**Main finished products (2)**
Mixed plastic waste	Pyrolysis (without fractionation)	Syncrude	To CDU	Diesel; jet; gasoline; other products light olefins. HCK – mainly dye
			To FCC	Gasoline; C3/C4 olefins (fuel-oil; coke; gas)
			To HCK	Diesel; jet; gasoline
Sewage sludge	HTL (without upgrading)	HTL oil	To hydrotreatment	Diesel (naphtha; fuel-oil)
			To FCC	Gasoline (fuel-oil; coke; gas)
			To HCK	Diesel; jet; gasoline
Mixed residual waste	Gasification + FT synthesis	FT syncrude	To CDU	Diesel; jet; gasoline; other products[2]
			To FCC	Gasoline; C3/C4 olefins (fuel-oil; coke; gas)
			To HCK	Diesel; jet; gasoline
Municipal biowaste (including food and garden waste)	AD + steam reforming + FT synthesis	FT syncrude	To CDU	Diesel; jet; gasoline; other products
			To FCC	Gasoline; C3/C4 olefins (fuel-oil; coke; gas)
			To HCK	Diesel; jet; gasoline

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[2] 'Other products' includes chemical naphtha, heating oil, marine fuel, lubricants

3 WTF REFINERY PATHWAYS LITERATURE REVIEW (TASK 2)

Task 2 provides an overview of the key technology and supply chain (3.1), economics and financing (3.2), policy/regulatory (3.3) and sustainability (3.4) related aspects of the four chosen pathways, with the sub-sections of this section providing an insight into the key findings and knowledge gaps associated with each of these aspects.

3.1 TECHNOLOGY AND SUPPLY CHAIN

This part of the study is intended to explore the potential technical issues associated with bringing waste-derived liquids into the refined product supply chain using refinery process units (and blending facilities) to produce finished fuels.

The refined product supply chain comprises:

- Crude oil import – typically by pipeline (10s of kton/day) or ship (up to ~300 kton) delivering into a crude terminal or refinery tank farm, with large storage tanks (up to ~200 ktons).
- Refinery – receiving typically 20 to 50 kton/day of crude and making equivalent amounts of refined products and intermediate 'blendstocks' which are traded with other refineries.
- Product distribution – by tanker, barge, pipeline, or rail (often multi kton cargoes) to distribution depots or commercial users (e.g. airports), then typically road distribution to retail sites.

Today, the main fuel products include gasoline and diesel (roughly 20 % and 30 % of refinery output), followed by jet (10 %), light heating oil/marine diesel (10 %) and heavy fuel oils (15 %) for inland and marine applications. Refineries also provide petrochemical feeds (10 % of refinery output), typically propylene, naphtha for steam crackers and aromatics feedstock for the benzene/toluene/xylenes markets. Demand for gasoline and heating oil are declining (e.g. due to electrification), but demand for jet is increasing. Sulfur emission regulation may push the marine market from high-sulfur heavy fuel oil towards marine distillates and low-sulfur heavy fuel oil. Renewable content is already mandated for gasoline and diesel; there is interest in reducing the carbon intensity of other fuels.

This section therefore considers (1) the type of waste, the technology used to convert it and the nature of the primary product; (2) refinery technologies which can use the primary product and the nature of their products; (3) how this might integrate into the overall fuel supply chain, and (4) the technical and commercial readiness of each pathway. In each of these subsections, a high-level commentary of the issues is provided in the form of tables; further supporting information can be found in Annex B. This section concludes with a summary of the key findings and highlights knowledge gaps where further investigation is needed.

3.1.1 Waste type and primary conversion technologies

This report addresses four general pathways, whilst recognising that specific technology choices (e.g. type of gasifier) depend on the details of specific feeds (e.g. different wastewater treatment technologies could lead to different levels of ash and grit in the sludge and hence different choices for pre-treatment and HTL plant design). In addition, the 'waste-supply chain' may lead to variable feed quality, although this might be partially mitigated by sorting (especially plastics waste), aggregation and mixing (especially residual wastes) or source segregation (especially food/garden wastes.) There is more discussion about this in Annex A.

The product quality from primary conversion determines how it can be integrated into the refined product supply chain, in particular the type and degree of upgrading. The primary products from the FT pathways (MRW; food/garden waste) and from (O/N/Cl-free) waste plastics are hydrocarbons which only require fractionation into appropriate boiling ranges (e.g. gasoline; diesel; wax) before use at low blend levels. On the other hand, they may require additional treatment (hydrotreatment/HCK) before use at high blend levels. HTL-oil derived from sewage sludge contains both hydrocarbons and non-hydrocarbons (e.g. fatty acids, phenols, amides) and requires deoxygenation and fractionation before use as transport fuel. (Note that HTL-oil has a much lower oxygen content than biomass fast-pyrolysis oil (e.g. 5–10 % vs 40–50 %) so ought to be much easier to handle and upgrade.)

This study is aimed at exploring potential synergies between primary conversion and crude oil refining, and so focuses on primary products which have not yet been upgraded. On the other hand, a primary conversion plant could be equipped with product upgrading technology, in which case the products would be 'drop-in' fuel blend stocks that require no further processing.

Table 6 summarises the main considerations associated with the primary conversion step in each pathway, particularly important feed and product characteristics. The latter include both bulk-chemistry which affects transport fuel yield/quality and impurities which might affect the ease with which they can be upgraded to transport fuels. For example, impurities might lead to corrosion or fouling of refinery equipment, and lead to deactivation of refinery catalysts; more detail is provided in Annex A and Annex B, and implications discussed in subsequent sections.

Table 6: Characteristics of the primary conversion step

Pathway	**Factors which affect primary conversion part of supply chain**		
	Waste characteristics	**Choice of primary conversion technology**	**Primary product characteristics**
Mixed plastic waste via pyrolysis	Mainly polyolefins (high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP)) sorted to minimise impurities, including: (a) polystyrene (PS) & PDMM which react differently, (b) polyvinyl chloride (PVC) which creates operational problems, (c) polyethylene terephthalate (PET) which is better recycled separately	Specialised plastics pyrolysis technologies with characteristics which may be suited to different polymer mixes and target products, e.g. (a) polyethylene (PE)/ PP + different levels of PS; (b) product boiling range and hydrocarbon composition (especially aromaticity; olefinicity)	Wide-boiling hydrocarbon spanning gasoline, diesel, and heavier boiling fractions. Mainly aliphatic with variable aromatic content (~5–25 %). Aliphatics include olefins which are good for gasoline octane but may impair storage stability. Olefins/stability might limit use at high blend levels in diesel. Potential for contaminants, e.g. S, N, O-containing species and particulates and metals
Sewage sludge via HTL	Mixed fats, proteins, carbohydrates from wastewater-treatment plant. Main variabilities likely to be (a) scale 10 to 100 ton/day (b) ash/grit content 10–40 %	Hydrothermal liquefaction is well suited to 'wet' feeds, e.g. 25 % solids. Current technology is mainly aimed at woody/green biomass, but likely to be applicable to sludges	Wide-boiling oil containing 5 to 10 wt% oxygen + N/S/P-containing compounds (hydrocarbons, fatty acids, phenols, amides). Other potential issues include acidity/corrosivity and particulates and metals.
Mixed residual waste via gasification (and FT synthesis)	Mixed organics and inorganics, e.g. metals, concrete, glass. Composition, moisture content and particle size could be highly variable	Moisture content and coarse particles would not suit entrained-bed gasifiers; some fluid bed gasifier types may be suitable; plasma gasifiers likely to be suitable	FT diesel and naphtha resemble their fossil counterparts; FT-wax/ syncrude is usually a solid at ambient temperature so may need heated storage. All are 100 % hydrocarbon

Table 6: Characteristics of the primary conversion step (continued)

Pathway	Factors which affect primary conversion part of supply chain		
	Waste characteristics	**Choice of primary conversion technology**	**Primary product characteristics**
Municipal biowaste (including food and garden waste) via AD	Very broad waste category, e.g. consumer vs factory food-waste; leafy vs woody mixed garden waste. Uncertainty over water content. Both could contain non-digestible materials, e.g. plastics	AD already deployed at commercial scale for feed-wastes and segregated plant materials, e.g. silage and energy crops. Heterogeneity will be a big factor in process choice, e.g. 'wet' vs 'dry' AD vs composting	See 'Mixed residual waste via gasification'

Note that examination of the feedstock supply chain is not within scope of the study; however, some of the key issues are highlighted as follows:

Mixed plastic waste:

- Established supply chains already exist where mixed plastic waste streams are collected from MRFs and sent to landfill or EfW.
- MRFs are not designed to produce a mixed plastic waste stream that is tailored to the needs of pyrolysis plants. Contaminants in the waste feedstock can cause reliability issues for pyrolysis plants.
- Mixed plastic waste is generally more expensive to transport compared to pyrolysis oil (*Plastics to oil products*), owing to its lower energy density, which potentially supports locating pyrolysis units close to where the waste is located.

Sewage sludge:

- Established supply chains already exist where sewage sludge is collected from sewage treatment plants and sent for land application.
- Studies (Pacific Northwest National Laboratory (PNNL) *Conceptual biorefinery design and research targeted for 2022: hydrothermal liquefaction processing of wet waste to fuels*) assume that sludge processing would be co-located with the water-treatment plant in order to avoid transport of wet sludge. Given that the geographical concentration of sewage sludge is not expected to be very high, the economically viable feedstock sourcing radius potentially limits the size of the HTL units.

Mixed residual waste:

- Established supply chains already exist where MRW streams are collected from households and sent to landfill or EfW.
- MRW is processed into refuse-derived fuel (RDF), for which there is competition from other technology types such as fluidised bed energy from waste plants and cement kilns.

- A lack of standards for refuse-derived fuels leads to an inconsistent feedstock which can cause operational issues (Department for Environment, Food and Rural Affairs (Defra), *Refuse derived fuel market in England*).

Municipal biowaste:

- Established supply chains already exist where food and garden waste are collected from households and sent to AD/composting.
- Collection procedures (e.g. degree of segregation of food and garden waste) affects the feed composition (e.g. water, solids, and lignin content), which affects the suitability for type of AD treatment required.

A thorough examination of these supply chains is needed to better understand the scalability of these supply chains and has been recommended as an area for further study beyond the scope of this work.

3.1.2 Refinery conversion technologies

Europe has about 80 refineries which vary by size from less than 50 kbbl/day (7 ktonne/day) to more than 400 kbbl/day (55 ktonne/day), by design and by market (e.g. gasoline- vs diesel-oriented; with or without petrochemicals; coastal vs inland; merchant vs linked to local marketing and distribution). Some basic principles are common to all: crude oil is distilled into fractions which are processed either to improve their properties or to make more valuable streams, then blended into finished products. Although crude oils typical make up >80 % of the intake, many refineries also process crude-derived intermediates from other refineries (e.g. residues, gas-oils, and gasoline-range stocks) or by-products from petrochemicals of natural-gas processing (e.g. raffinates, steam-cracker pyrolysis oils, natural gas condensates). The key entry points for the intermediate products into a refinery are (a) CDU; (b) boiling-range conversion units such as FCC and HCK; (c) quality upgrading units such as naphtha hydrotreater (NHT) and distillate hydrotreater (DHT), and (d) final product blending, as shown in Figure 1. Refineries today use all four as entry points for imported fossil feed- and blendstocks; it would be much the same for waste-derived products.

The choice of entry point depends on the amount and the properties of the waste-derived import. If the imported feed is a 'syncrude' with a wide boiling range that spans several products, then it might be thought that the CDU would be a good choice. It can provide 'desalting' to remove impurities and also separates the syncrude into fractions for upgrading or conversion. The CDU is, however, the 'heart' of the refinery, so major considerations include: (a) the risk of damage or process upsets if the imported feed is corrosive or might lead to fouling, and (b) the wide range of paths that alternative materials might take through the refinery after leaving the CDU. The second point means that the CDU is not appropriate for feeds which are not 100 % hydrocarbons (e.g. HTL-oil). Having multiple pathways increases the complexity of a risk assessment and makes it harder to determine how much alternative material is in each of the refinery products. Operating at low syncrude:crude ratio might reduce the risks but also reduces any benefit of processing the alternative feed.

If the syncrude contains a lot of high-boiling material (e.g. >350 °C), then it might be better to route it to a 'conversion' unit such as FCC or HCK. In Europe, around half of refineries have FCC, a third have HCK, and around a quarter have both. FCC is generally viewed as the more robust process, capable of handling poorer quality feeds or feeds with higher contaminant levels, but on the other hand, it is gasoline-oriented and makes low-value co-products such as fuel-oil, coke, and fuel gas. HCK is more sensitive to feed quality but makes excellent diesel and jet although at the expense of high hydrogen consumption.

If the primary product already has the right boiling range and only requires upgrading to improve its properties, then it might be routed directly to an appropriate process unit. A good example practised today is the hydrodeoxygenation of vegetable oil by co-processing in a refinery diesel hydrodesulfurisation unit. Direct blending is only appropriate if the imported feed has already been upgraded and fractionated to finished fuel blending standard. It does not necessarily have to meet an accepted fuel specification (e.g. EN 228 *Automotive fuels - Unleaded petrol - Requirements and test methods* or EN 590 *Automotive fuels - Diesel - Requirements and test methods*), but the closer the better.

The choice and degree to which these entry points are used depends on feedstock quality limits set by individual refineries and the level at which the waste-derived products will be used. The key issues therefore are boiling range, bulk composition (molecule types) and impurities, which are discussed in Annex B and summarised in Table 7.

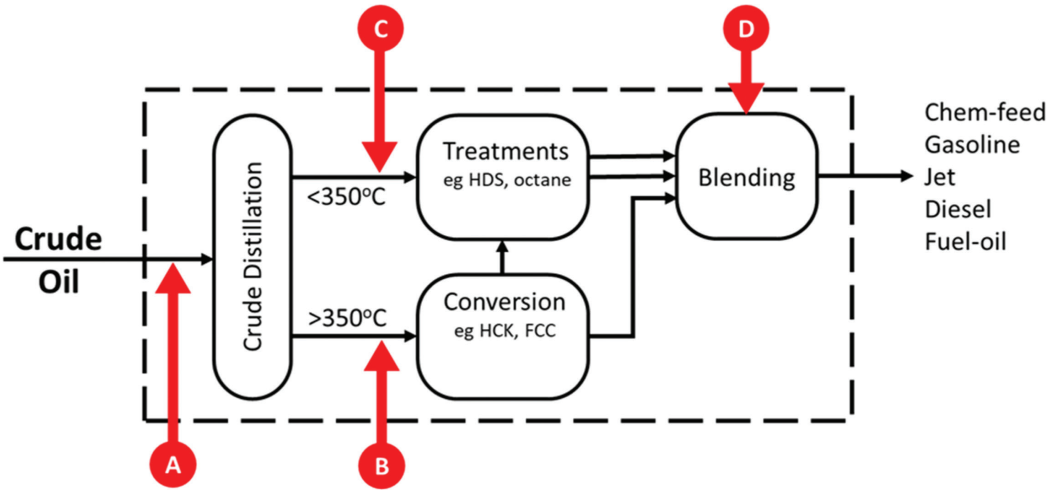

Figure 1: Key entry points for intermediate products into refineries

A noticeable aspect of three pathways (mixed plastic/pyrolysis; MRW/gasification/FT; food/garden waste/AD/FT) is that the intermediate product is a hydrocarbon-like 'syncrude' whose boiling range and detailed properties are highly technology-dependent. Sewage-sludge/HTL is different – it requires hydrodeoxygenation, fractionation, and possibly some conversion before use as fuel blend stock.

If refinery processing is required, then different approaches will need to be considered, which vary depending on the amount of intermediate product to be used in a refinery:

- Co-feed, where a relatively low proportion (e.g. a few %) of waste-derived feed and fossil-feed is fed to an existing refinery process unit.
- Unit modification, to allow for a relatively higher blend (e.g. a few 10s of %) of waste-derived feed and fossil-feed to be fed to an existing refinery process unit.
- Unit repurposing via major modifications, which allows an existing process unit to be switched to 100 % waste-derived feed.
- Unit hosting, where a dedicated/specialist upgrading unit such as an HTL-hydrotreater is co-located at a refinery to make use of its infrastructure, e.g. supply of hydrogen, off-gas handling, product logistics.

(Note: the feed blend amounts for co-feed and unit modification are indicative values; in reality, limits depend on the specifics of feed-properties and unit design. It is discussed in more detail in Annex B).

Table 7: Suitability of the products from the wastes and primary conversion technologies for refinery processing

Pathway	Factors which affect refinery processing		
	Refinery pretreatment	**Use of refinery equipment**	**Blend limits (or other refinery impacts)**
Mixed plastic waste via pyrolysis	Similar to hydrocarbon fuels; long-term storage may be an issue due to olefins content. Also, particulates, trace metals, residual chlorine and oxygenates from PVC, PET, polymethyl methacrylate (PMMA)	At low levels it might only require fractionation, e.g. co-feed to CDU subject to stability of streams, fouling, corrosion, or catalyst deactivation. At higher levels, it might need hydrotreatment to reduce olefinicity. Higher boiling fractions are likely acceptable as feed for HCK (to make diesel) or FCC (to make gasoline + light olefins)	Untreated pyrolysis oil may be acceptable as process co-feed at >10 % in diesel hydrotreaters and HCK subject to boiling range, composition, and contaminant levels. FCC will be more tolerant of pyrolysis oil impurities, but potential to form coke and light gases is not known Gasoline fraction is likely to have good blending properties. Diesel fraction may be usable at low levels, but olefin content might limit use at higher levels. Both are subject to impurity levels (e.g. S, CL, acids) and stability
Sewage sludge via HTL	Main issues are water and solids content; acidity could be high (e.g. acid number of 10–50 mgKOH/g compared with <5 desired for use as refinery co-feed	Requires deoxygenation so cannot use CDU. Hydrotreating for oxygen, sulfur, and nitrogen removal; HCK for conversion of heaviest fraction. Processing levels might be limited by impurity levels, e.g. risk of fouling, corrosion, or catalyst deactivation. The impact of the use of FCC for converting HTL-oils is unclear	Raw (untreated) HTL oil may be suitable for use as process co-feed possibly limited by hydrogen consumption (linked to oxygen content), impurities and flow-properties Hydrotreated gasoline fraction may have relatively low octane; hydrotreated diesel fraction may contain high boiling material. Aromatics levels probably acceptable for both fuels

Table 7: Suitability of the products from the wastes and primary conversion technologies for refinery processing (continued)

Pathway	**Factors which affect refinery processing**		
	Refinery pretreatment	**Use of refinery equipment**	**Blend limits (or other refinery impacts)**
Mixed residual waste via gasification (and FT)	FT-syncrude probably needs no chemical pretreatment to remove impurities; it comprises waxy paraffins so care may be needed to avoid stability issues when co-feeding with crude-derived blend stocks	CDU may be acceptable at low levels subject to flow properties. FT-syncrude is best converted by HCK which gives high-quality diesel and jet – but as yet there is little information about co-processing in refinery units. Co-feed to FCC likely makes gasoline + light olefins but also light gas and coke	Limits for co-feeding FT syncrudes to HCK or FCC are likely to be unit-specific, subject to both process operation and final product properties. It would be expected that co-processed FT products would have good blending properties but may have case-dependent limits. For example, regulations currently set a 50 % maximum for FT material in Jet-A1. – Cold-flow properties might limit blend content in diesel at some refineries, although the low density might create a crude-quality opportunity at others. The use of FT-naphtha in gasoline may be limited by low-octane rating
Municipal biowaste (incl. food and garden waste) via AD	See 'Mixed Residual Waste via gasification'	See 'Mixed Residual Waste via gasification'	See 'Mixed Residual Waste via gasification'

3.1.3 Options and potential for supply-chain integration

This section explores the options and potential to link the WTF and crude oil supply chains, (e.g. *Waste recycling: an opportunity for refiners?*). The WTF supply chain includes waste collection and aggregation, primary conversion, and primary product distribution, but only the last two steps are within scope. In a similar vein, the study only considers the downstream part of the crude supply chain, i.e. from refinery import-storage tanks to fuel distribution depots. In addition to crude oil, refineries often trade refinery intermediates (e.g. gasoil, atmospheric residue) and fuel blendstocks (e.g. alkylate, reformate) where one refinery may have a surplus, and another has spare processing capacity or better options for product blending. These intermediates and blendstocks would be introduced at the entry points discussed in Figure 1. The full supply chain might also include standalone traders and blending plants who buy blendstocks from refiners and assemble them into finished fuels. The network is connected by various means, e.g. product pipelines, barges, and rail.

A key factor here is scale. EU refineries typically process 20 to 50 kton/day of crude and make 4 to 10 kton/day of gasoline and 5 to 20 kton/day of distillates (mainly road-diesel but also some heating oil and marine-diesel.) The major refinery process units are correspondingly large, with CDUs up to perhaps 20 kton/day and hydrotreaters, hydrocrackers and FCC units up to perhaps 10 kton/day.

The main issues around supply-chain integration are:

- Scale of primary production – most current examples are small in relation to oil-refinery capacities, so might indicate a decentralised model for the supply chain, wherein smaller, decentralised primary conversion units provide intermediate products as feedstock to a single refinery. It seems likely that primary process scale is limited by the resource (e.g. size of wastewater treatment plants supplying sewage sludge) and the difficulty of waste aggregation at large scale, due for example to the cost of transporting materials with low energy density. Process engineering fundamentals (e.g. heat transfer) apply differently in different pathways, e.g. AD may have a maximum practical size, but gasification may have a minimum practical size; this is discussed in Annex B.
- Shipment and storage of primary conversion products – products which resemble hydrocarbon fuels might be able to use fossil-logistics and storage systems, but others may require dedicated systems. Some intermediates may have special requirements, e.g. corrosion-resistant, inert-blanketed, or heated storage. Technical factors include presence of impurities (e.g. particulates; water; fouling potential; stability; contaminants, e.g. physical properties (e.g. melting point; viscosity), and safety (e.g. flashpoint, toxicity, corrosivity). Segregation might also be needed for issues such as taxation and confirmation of origin.

Table 8 highlights scale- and technical-compatibilities and their implications for logistics synergy/mismatch.

Table 8: Factors affecting supply chain integration for the selected waste types

Pathway	Factors which affect integration with refined product supply chain		
	Scale compatibility	**Technical compatibility**	**Logistic synergies or mismatch**
Mixed plastic waste via pyrolysis	Current plants are ~20–90 ton/day of products with some planned plants mainly up to 200 ton/day, i.e. an individual WTF plant is thus a few percent of a refinery's fuel production	Untreated plastics pyrolysis oil is hydrocarbon-like, subject to oxidation stability (high olefins) and potential for contamination and possibly corrosion (e.g. S)	Individual WTF plants are small compared with refined product supply chain; olefinic products may need segregated storage, e.g. inert blanketing for long-term storage
Sewage sludge via HTL	Current HTL plants' design studies typically describe plants of ~10 ton/day of products, i.e. <1 % of refinery fuel production	Oxygen content may make untreated HTL oil insufficiently hydrocarbon-like; also need to consider contaminant levels, acidity	HTL oil probably needs dedicated logistics and storage
Mixed residual waste via gasification	Current first of a kind commercial (e.g. Fulcrum) is ~100 ton/day, i.e. few percentages of refinery fuel production; similar plant scales using biomass/ FT or municipal solid waste (MSW)/methanol	FT diesel and naphtha resemble their fossil counterparts; FT-wax/ syncrude is usually a solid at ambient temperature. All are 100 % hydrocarbon	FT diesel and naphtha can use fossil supply-chain; FT-wax/syncrude may need dedicated system, e.g. heated tanks
Municipal biowaste (incl. food and garden waste) via AD	A conventional AD plant capacity could only supply a very small FT plant, i.e. ~5 ton/day products	See 'Mixed Residual Waste'	See 'Mixed Residual Waste'

3.1.4 Technical and commercial readiness

All the individual technologies described here have been operated at demonstration-scale or higher, but none of the *integrated* pathways has been operated at large commercial scale. Some key uncertainties are:

– Complex multi-step pathways – individual multiple steps may have been demonstrated, but few have been demonstrated together. For example, AD is widely practised and FT technology is commercial at large-scale; on the other hand, integrated AD-FT has yet to be demonstrated. Conversion of FT-wax into fuel products is practised commercially in large-scale dedicated gas-to-liquid (GTL) facilities, but co-processing of FT-wax in refineries is still at early demonstration-scale.

– Operation at scale – there are some commercial examples, e.g. plastic energy is supplying diesel blendstocks derived from waste-plastics; Fulcrum is preparing to supply a Marathon refinery with FT-Syncrude derived from MSW. However, these are at a relatively small-scale in relation to the partners' overall fuel production and scale-up issues might not yet be apparent.

Further details of these issues for each pathway are described in Table 9.

Table 9: Technical and commercial status of each pathway

Pathway	State of technical and commercial activity		
	Primary conversion	**Refinery processing**	**Integrated supply chain**
Mixed plastic waste via pyrolysis	Several small plants operating, 20–90 ton/day, e.g. Plastic Energy	Not demonstrated. (Refinery processing might not be needed at low blend levels)	A few commercial examples at low-blend level
Sewage sludge via HTL	Small demo plants operating with biomass; none with sewage sludge although one may be planned (Steeper/Edmonton)	Standalone hydrotreatment has been demonstrated at pilot-scale; refinery co-feed is still at R&D scale	No examples
Mixed residual waste via gasification	Gasification of waste for power generation is commercial; integration of waste gasification and synthesis is still at demo-scale	Commercial blending of GTL-FT products. A demo of low-level refinery processing of FT-syncrude is planned (Fulcrum Sierra/Marathon)	Use of imported GTL-FT diesel is well-known in EU refineries Planned demo of FT-wax integration (Fulcrum Sierra /Marathon).
Municipal biowaste (incl. food and garden waste) via AD	'Wet' and 'dry' AD for biogas and power is commercial; integrated AD and fuel synthesis is still R&D	See 'Mixed Residual Waste'	See 'Mixed Residual Waste'

Plastics pyrolysis is the only pathway where primary conversion and fuel use are commercial today, but only at a handful of primary plants, and probably at low blend levels. For example, Plastic Energy offers gasoline-, diesel- and fuel-oil range materials which are reported to go to Repsol; there is little information about refinery processing and blending at higher levels. MRW gasification and municipal biowaste AD are both commercial for power but not for fuel synthesis. FT fuel synthesis technology is commercial at large scale using natural gas (e.g. >10 kton/day), but downsized versions are only just being demonstrated with examples between 0,3 and ~100 ton/day (Annex B). Refinery blending of natural-gas derived FT products is commercial, but there is little public information about refinery co-processing of FT-syncrude. Sewage-sludge/HTL appears to be only at pilot-scale for primary conversion.

3.1.5 Key findings and knowledge gaps

The key findings and knowledge-gaps relating to the technical and supply chain issues of the individual pathways have been summarised as follows:

Mixed plastic waste/pyrolysis/refining:

Findings: this is the only pathway where primary conversion is commercial today, but only at a handful of plants and at scales much smaller than typical refinery production. Catalytic pyrolysis lags behind thermal pyrolysis in term of commercialisation. The quality, yield, and gasoline: diesel split of primary product seems to depend on both plastic-feed composition (e.g. PE/PP ratio) and process design (e.g. temperature, residence times, post-treatments). Primary products seem to be usable in gasoline or diesel blends at low-levels (e.g. few %), subject to issues such as sulfur content and stability.

Knowledge gaps: it is unclear whether primary plant scale is limited by feedstock availability or process technology. There is little information about refinery processing and blending at higher levels, for example corrosion, fouling, heat release, product quality.

Sewage-sludge/HTL/refining:

Findings: primary conversion (HTL of sewage sludge) appears to be at pilot-scale but is closely related to HTL of wood residues which is at demo/small-commercial-scale. The HTL primary product seems to be less acidic, easier to handle and easier to upgrade than thermal fast-pyrolysis oils, but still requires upgrading to remove residual oxygen. Hydrotreated product is mainly in the diesel range but contains gasoline and fuel-oil fractions. Operating scale for primary conversion plants is likely to be limited by local sludge availability, suggesting a 'hub' model for upgrading to finished blend stocks using either standalone hydrotreating or refinery processing.

Knowledge gaps: there is little information about the use of upgraded products at high-blend levels or about co-processing for refinery upgrading.

Mixed residual waste/gasification/FT-synthesis/refining

Findings: MRW-gasification is commercial for power generation. Natural gas and coal-based FT-synthesis is commercial but at much larger scale; upgraded FT-products (naphtha and diesel) are already used in the refined product supply chain. There are several downscaled FT-technologies at large-pilot/small-demo scale, e.g. targeting biomass- and flare-gas conversion. Commercial demonstration of integrated MRW-gasification with downscaled FT synthesis is imminent, but at a scale which is much smaller than conventional refinery operations.

Knowledge gaps: there is little public information about progress in making gasification/ FT more flexible to handle variations in waste composition. There is little public information about the optimisation of FT technology to make 'refinery-processable' FT-syncrude or about co-processing FT-syncrudes in refineries. It is not clear what might be the likely scale of future MRW gasification/FT facilities.

Municipal biowaste (incl. food and garden waste)/AD/FT-synthesis/refining

Findings: AD conversion of food and biomass is commercial for production of biogas and power. The AD feed is typically segregated, e.g. food waste, farm manure, a well-defined biomass such as silage or an energy crop. There are already some commercial integrated AD/composting facilities probably using segregated AD and composting feeds; it is not clear if anyone is using AD for pre-mixed food- and garden-waste. Typical AD scale is very small compared with commercial-scale FT, but there are downsized FT-technologies under development.

Knowledge gaps: there is little public information about the optimisation of FT technology to make 'refinery-processable' FT-syncrude or about co-processing FT-syncrudes in refineries. It is not clear what might be the likely scale of future AD/FT facilities.

Key findings which apply to all pathways are:

- Most of the primary technologies already have commercial counterparts, although with different feedstocks to those specifically addressed in this study and are at a different scale. Technical development therefore is having to address re-scaling of individual process steps, development of integrated plant designs and process development to simplify small-scale process flow-schemes.
- Most of the primary technologies (gasification, AD, HTL, FT synthesis) are also being considered for other alternative resources (e.g. biomass, eFuel, flare-gas) potentially providing development synergies. Plastics pyrolysis technology has resource-based opportunity but may show synergy with plastics recycling to chemical feedstocks. All of the primary products are 'syncrudes' whose boiling range depends on the primary conversion technology and may require fractionation into gasoline and diesel; some require chemical processing, e.g. to remove oxygen, sulfur and other contaminants. This can be done at the primary plant (e.g. local hydrotreater) but current views about commercial scale suggest that centralised treatment would be more effective.
- For most pathways, there are several refinery processing options, each with a different balance of risk, yield, and product quality. The options and their balance depend on the design of the refinery and on the relative amounts of WTF feed and fossil crude. This also might provide some optionality for the refiner to swing between products (diesel vs chemical feed for example) depending on market conditions; this might not be something that a 'drop-in' WTF manufacturer could do.
- Current and planned commercial WTP plants are generally very small (5 to 150 ton/day) in relation to typical refinery crude rate (20 kton/day) and fuel production (e.g. 5 to 10 kton/day). Low level use (e.g. <5 %) where a refinery receives product from a single WTF-plant may allow considerable latitude in terms of primary qualities and contaminant levels. This might allow refinery processing/blending with relatively low investment (e.g. handling and storage) provided that the risk for refinery operations (e.g. corrosion, fouling, catalyst deactivation) and end-users has been mitigated.
- Higher level use (e.g. 10–30 %) might arise where upscaled WTF plant is feasible or where several WTF-plants supply a single refinery. This would place more stringent requirements on primary product quality/cleanliness and might require more modification to refinery units (e.g. guard beds to remove contaminants, hydrogen/feed ratio, catalyst optimisation).
- In principle, major investment might allow a refinery to be converted into a 'WTF-processing hub;' a handful of recent examples involves refineries closing much of their operation and converting the rest for biofuel production from well-defined feeds such as vegetable oils. WTF primary products are energy-rich and generally more easily handled than the wastes themselves which would facilitate the establishment of a wide-ranging supply system. On the other hand, it is not clear whether the potential supply of waste could support this.

Significant areas where further research is needed relate to the scale-up of these pathways beyond the small-scale demonstration projects observed currently, in particular:

- Impact on refinery operations if intermediate products are processed at high levels (e.g. 10–30 % of refinery process feed)
- Impact on final product quality when using higher levels of both waste-derived blend stocks and refinery products made from waste-derived feeds.

Scale-up of waste-derived product availability, both in terms of potential and in terms of heterogeneity of supply and management of variable waste-derived feed/product qualities.

3.2 ECONOMICS AND FINANCING

This section includes a summary of the cost drivers for each pathway, selected investment costs for projects related to these pathways and sources of finance. There are additional details on the cost drivers for each pathway in Annex C.

3.2.1 Cost drivers and investment costs

A summary of major cost drivers for each pathway is provided in Table 10. Each pathway table provides more information on how the capital expenditure (CAPEX), operational expenditure (OPEX) and feedstock major cost drivers affect each of the agreed pathways. They outline what the major drivers are, how they compare to fossil production (where relevant), or alternative feedstocks not covered in this study (such as biomass).

Table 10: Summary of major cost drivers for each pathway

Pathway	CAPEX	OPEX	Feedstock
Mixed plastic waste pyrolysis to pyrolysis oil refining	Pyrolysis reactor – these tend to be scaled to fit the local availability of feedstock. However, scale and therefore total project investment, could be limited by reactor size Due to olefin content and impurities refinery CAPEX may be required if the pyrolysis oil cannot be processed directly in existing units	Energy input is largely from the plastic waste feedstock. Most (often all) energy needed for the pyrolysis is contained within the plastic, and a significant proportion is used for this energy Where hydrotreating or HCK conversion processes are used, the hydrogen costs could be more than when processing fossil hydrocarbons where there is a higher level of impurities	Post-consumer mixed plastic waste (largely packaging) is the current focus. A gate fee, where applicable, can be an important factor for feedstock impact on economics

Table 10: Summary of major cost drivers for each pathway (continued)

Pathway	CAPEX	OPEX	Feedstock
Sewage sludge HTL to HTL oil refining	HTL reactor – the severe operating conditions result in high cost for the reactor. HTL plants are more scalable than pyrolysis plants and could potentially see more economies of scale savings in the future Due to oxygenates content and impurities refinery CAPEX may be required if the HTL oil cannot be processed directly in existing units	Net energy requirement is high – HTL requires significant quantities of heated and pressurised water, and this may represent a major cost driver, depending on the local energy costs and also the feedstock used Where hydrotreating or HCK conversion processes are used, the hydrogen costs could be more than when processing fossil hydrocarbons where there is a higher level of impurities	The cost of sewage sludge could be a major determinant of the process economics; however, it can be sourced at zero, low cost or sometimes a gate fee can be charged
Mixed residual waste gasification to FT-wax refining	Gasifier CAPEX is significant and varies with gasifier type and scale. Gas clean-up; depending on gasifier type employed, feedstock composition and requirements for downstream processing. The FT reactor is also expected to be a significant cost	The heat needed for the gasification reactions is usually provided by the partial combustion of a portion of the feedstock in the reactor The gasifier agent and its impact on downstream processing could be a significant cost, e.g. oxygen would be most expensive but offers operational benefits The FT catalysts are deactivated by sulfur poisoning, and this adds costs either in sulfur removal or, if it is not removed sufficiently, loss of catalyst activity and lifetime Where hydrotreating or HCK conversion processes are used, the hydrogen costs could be more than when processing fossil hydrocarbons where there is a higher level of impurities	The economics of plants using MRW depends on receiving gate fees for waste treatment, which vary considerably between jurisdictions

Table 10: Summary of major cost drivers for each pathway (continued)

Pathway	CAPEX	OPEX	Feedstock
Municipal biowaste (incl. food and garden waste) AD of biogas, to bioCH4, to FT-wax refining	The AD reactor is a large portion of the costs for this process step The FT reactor is expected to be a significant cost	The FT catalysts are deactivated by sulfur poisoning, and this adds costs either in sulfur removal or, if it is not removed sufficiently, loss of catalyst activity and lifetime Where hydrotreating or HCK conversion processes are used, the hydrogen costs could be more than when processing fossil hydrocarbons where there is a higher level of impurities	The AD producer receives a gate fee. This can become an important influence on the AD producer's economics

Project examples showing some typical sizes and CAPEX for different new WTF-related units that are operational, under construction or planned are shown in Table 11. There were no reference projects found for AD integrated with FT synthesis.

Table 11: Examples of CAPEX cost for projects related to each pathway

Primary Conversion(s)	Developing company	Organisations involved in project consortium	CAPEX (million EUR)	CAPEX (million)	CAPEX currency and year	Biofuel product(s)	Products capacity (kt/a)	Location	Feedstock	Feedstock capacity (kt/a)	CAPEX intensity (Million EUR/kt)	Project status
Pyrolysis to pyrolysis oil	Quantafuel	Vitol, BASF	14,8	17,5	USD, 2018	Diesel, gasoline, fuel oil	13,1	Skive, Denmark	Plastics	20,0	0,74	Operational
Pyrolysis to pyrolysis oil	Recycling technologies	Recycling Technologies, Binn group, Zero Waste Scotland	5,7	5,0	GBP, 2018	Gasoline, jet, diesel	5,3	Perth, UK	Plastics	7,0	0,81	Under construction
HTL to HTL oil	Genifuel Corporation	PNNL (technology), Zeton Inc. (Canada)	4,7	5,5	USD, 2018	Biocrude	0,3	Vancouver, Canada	Waste (feedstock volumes are wet)	3,2	1,46	Under construction
Gasification + FT to wax	Fulcrum Bioenergy Inc.	TRI (ThermoChemi Recovery International), Air BP	180,0	200,0	USD, 2015	FT diesel, jet	31,0	McCarran, USA	Waste	157,5	1,14	Under construction
Gasification + FT to wax	Velocys	TRI, and in talks with several more potential partners	265,8	300,0	USD, 2017	Diesel or jet fuel	31,0	Natchez, USA	Lignocellulosics	252,0	1,05	Planned

Sources: Company press releases, E4tech Advanced Fuels database. Note: annual average historical exchange rates used

3.2.2 Sources of finance

An overview of public and private sources of finance in the EU, with examples of projects that have been financed via these means is provided in Table 12.

Table 12: Summary of the sources of finance in the EU

Type	Typical type	Typical stage	Examples
Venture capital	Equity	Pilot or demo	European Circular Bioeconomy Fund, Earth Capital, FullCycle Fund, Armstrong Capital (Example: Armstrong Capital have invested in ReNew ELP – plastic waste HTL)
Crowdsourcing	Equity or project finance	Pilot, demo or FOAK commercial	Seedrs, Abundance
Public	Grant	Pilot to demo	EU Horizon 2020, Innovate UK (Example: CLARA – chemical looping gasification for sustainable production of biofuels)
Public	Loan guarantee	Demo or commercial scale plants	US Department of Agriculture's Rural Development (Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program)
Strategic	Equity or project finance	Demo or commercial scale plants	Oil companies (e.g. BP, Shell, Repsol, Neste), Chemical/polymer producers (e.g. INEOS, SABIC) (Example: SABIC and Plastic Energy)
Multilateral development banks	Project finance	Demo or commercial scale plants	European Bank for Reconstruction and Development (EBRD), European Investment Bank (EIB)
International banks	Project finance	Demo or commercial scale plants (less likely FOAK)	Barclays, HSBC, JP Morgan Chase, Citi

3.2.3 Key findings and knowledge gaps

A number of key findings relating to the cost drivers associated with these pathways were observed:

- The expected significance of local, project-specific factors that could influence both the OPEX and feedstock cost drivers.
- The importance of feedstock for all routes, in particular those routes that also use the feedstock as the major energy source for the primary conversion step (pyrolysis and gasification).

- In some countries and for some waste feedstocks, gate fees[3] are an important determinant of how the feedstock influences both the primary process step (e.g. pyrolysis) and the overall economics of the pathways. Gate fees vary considerably between country, waste treatment type, and waste type. In some countries, these gate fees are published. For example, in the UK, Waste and Resources Action Programme (WRAP) publishes yearly averages. In some cases, gate fees can be negative (i.e. the waste processer pays to take the material), but are more usually positive.

The following key knowledge gaps emerged from this work:

- Feedstock costs, policy and gate fees for these wastes are geographically dependent, significantly more so than for fossil feedstocks that are generally widely traded commodities. Therefore, the knowledge gaps on feedstock costs relate to identifying an understanding of these at a more geographical-specific level. This is something that would be crucial to help identify locations where scale-up of these value chains could be most viable.
- For CAPEX, there is limited information on the impact of different gasifier types on CAPEX and how the economics are impacted by these, the feedstock and the trade-off between syngas clean-up and FT catalyst replacement costs.
- There are project references for the pyrolysis pathway, the HTL pathway (but not using sewage sludge), and the gasification pathway, but no reference projects found for AD integrated with FT synthesis.

3.3 POLICY/REGULATION

A review of EU legislation, related national regulations, and voluntary initiatives was carried out to evaluate the risks and opportunities that may affect the selected WTF pathways at present and in the future. The policies that were reviewed in this study are summarised in Table 13 grouped by the waste feedstock(s) that are affected. Some of these policies affect feedstock availability while others influence the demand for fuel derived from the waste feedstocks. These effects may be positive; for example, increasing feedstock availability, thereby promoting the WTF pathways. Alternatively, the effects may be negative; for example, diverting more feedstock towards another waste management option and away from the WTF pathways.

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[3] A gate fee (or tipping fee) is the charge levied upon a given quantity of waste received at a waste processing facility.

Table 13: Summary of the policies reviewed, categorised by waste feedstocks and type of effect whether that is related to feedstock availability or fuel demand

Waste feedstock	Policy (*denotes voluntary initiatives)
Policies that affect fuel demand	
Potentially all wastes	RED II
	Fuel Quality Directive
	Fuel EU Maritime Initiative
	Sustainable Aviation Fuels mandate
	Sustainable finance taxonomy
	EU ETS
	Industrial Emissions Directive 2010/75/EU
Policies that affect feedstock availability	
All wastes	Regulation 1013/2006 on shipments of waste
	Waste Framework Directive 2008/98/EC
	Incineration tax
Mixed residual, mixed plastic and municipal biowaste (incl. food and garden waste)	Directive 2018/850 on landfill of waste
Mixed residual and mixed plastic waste	Directive 2018/852 on packaging and packaging waste
	Extended Producer Responsibility (EPR) reform
Mixed plastic waste	Plastic packaging tax
	EU Strategy for plastics in a circular economy
	Directive 2019/904 on the reduction of the impact of certain plastic products on the environment
	Ellen MacArthur Foundation*
	Circular Plastics Alliance*
Municipal biowaste (incl. food and garden waste)	Farm to fork strategy
Sewage sludge	Directive 91/271/EEC on wastewater treatment
	Directive 86/278/EEC on sewage sludge
Effect of policy on WTF pathways unclear	
Feedstock(s) unknown	End of waste (EoW) criteria

3.3.1 Summary of policies

The impacts that the policies have, or could potentially have in the future, on the selected WTF pathways were identified and are summarised in Table 14. To rank the severity of the impacts of the policies reviewed, the following were considered:

- the number of waste feedstocks that would be affected;
- the type of action promoted (mandatory or voluntary), and
- competition from alternative waste management options.

Further detail has been provided for specific policies in Annex D.

Table 14: Summary of key policies that impact the selected pathways

Policy name (*voluntary initiatives)	Summary of policy	Waste stream(s) affected	Potential impact on the pathway(s)	Impact severity	Knowledge gaps
Policies that affect fuel demand					
Renewable Energy Directive (RED II) (European Commission, 2018)	Member states (MSs) are obligated to supply 14 % of transport energy from renewable sources, including 1,75 % of transport energy from advanced biofuels which can be double-counted to meet the overall targets	The biogenic fraction of MRW, sewage sludge and municipal biowaste count as advanced	Encourages uptake of WTFs to meet renewable transport targets	High (positive)	Criteria for recycled carbon fuels still under review – which includes mixed plastic waste and the non-biogenic fraction of MRW
Fuel Quality Directive (FQD) (European Commission, 2016)	Obligates fuel suppliers to reduce transport fuel GHG emissions by at least 6 % by 2020 compared to 2010 and maintain this beyond 2020	MRW, municipal biowaste and sewage sludge	There is support for biofuels which can be produced from wastes. This policy could encourage production of fuels from waste origin to meet fuel quality targets	High (positive)	Unclear if this policy would support recycled carbon fuels
Fuel EU Maritime Initiative (European Commission, 2020)	Increase the use of sustainable alternative fuels in European shipping and ports	Potentially all waste pathways	Has the potential to encourage demand for fuel produced via the WTF pathways to meet marine fuels targets.	High (positive)	Unclear on policy measures that will be used, as currently undecided
Sustainable Aviation Fuels (SAF) mandate (European Commission, 2020)	Increase the production and use of SAF to contribute to aviation decarbonisation	Potentially all waste pathways	Has the potential to encourage demand for fuel produced via the WTF pathways to meet aviation fuels targets	High (positive)	Policy is currently under development

Table 14: Summary of key policies that impact the selected pathways (continued)

Policy name (*voluntary initiatives)	Summary of policy	Waste stream(s) affected	Potential impact on the pathway(s)	Impact severity	Knowledge gaps
Sustainable finance taxonomy – Regulation (EU) 2020/852 (European Commission, 2020)	Defines the criteria that an economic activity must meet to be classed as environmentally sustainable to be eligible for financing	Potentially all waste pathways	Manufacture of biogas or biofuels meets some of the criteria required so this policy may provide financial incentive to the biogenic waste pathways. The use of waste to replace virgin raw materials, including fossil-based products in transport, is recognised as contributing to climate change mitigation in the draft regulation (European Commission, 2020)	High (positive)	Replacing fossil-based products with waste for transport may be considered sustainable under this taxonomy. However, it is unclear if all the WTF pathways would be eligible. The regulation is expected to be finalised by 2022
EU ETS (European Commission, 2020)	Emissions trading system which requires certain activities to purchase GHG emission permits	MRW and mixed plastic waste	Dependent on MS allocation of emissions, WTF pathways may be subject to greater costs and restrictions at the plant production level Biogenic emissions are not affected by this scheme, as well as incineration of municipal waste, meaning diversion of waste to produce recycled carbon fuels (RCFs) is not encouraged by the EU ETS	Medium (negative)	Likely this applies to the WTF pathways but still some uncertainty
Industrial Emissions Directive 2010/75/EU (European Commission, 2011)	Key reference for the regulation of pollutant emissions from industrial installations	Potentially all waste pathways	May encourage uptake of the technologies in the WTF pathways if they have lower emissions compared to other waste treatment methods	Medium (positive)	Impact of this directive on the integrated WTF pathways (including primary conversion and refinery steps) will need to be reviewed

Table 14: Summary of key policies that impact the selected pathways (continued)

Policy name (*voluntary initiatives)	Summary of policy	Waste stream(s) affected	Potential impact on the pathway(s)	Impact severity	Knowledge gaps
Policies that affect feedstock availability					
Regulation 1013/2006 on shipments of waste (European Commission, 2006)	Rules for the transport of waste within and beyond EU borders to protect the environment and public health	Potentially all waste pathways	May reduce availability of waste feedstocks imported from certain countries due to consent being required for the shipment of waste across borders	High (negative)	Unclear how this regulation applies to the WTF pathways with the recovery for fuel production EoL fate
Plastic packaging tax (European Council, 2020)	0,80 €/kg tax on non-recyclable plastic packaging waste from 1 January 2021	Mixed plastic waste	More plastic waste may be diverted to recycling, so less for recovery	High (negative)	
Directive 2018/852 on packaging and packaging waste (European Commission, 1994)	By weight at least 65 % of all packaging will be recycled by 2025 and at least 70 % by 2030	MRW and mixed plastic waste	Currently 19 % MRW is recycled (Eurostat). More waste will be diverted to recycling and less will be available for recovery	High (negative)	
Extended Producer Responsibility (EPR) reform in Directive 2008/98/ EC amended by Directive 2018/851 (European Commission, 2018)	The producer responsibility is extended to post-consumer (EoL costs of packaging materials at the collection and sorting stage), but it is left for MS to apply in national legislation	MRW and mixed plastic waste	Proven to be effective in increasing packaging recovery rates where an effective regulatory framework has been established (Gupt & Sahay). Collection and separation are likely to reduce the amount of MRW available. More plastic waste will be collected but recycling is favoured	High (negative)	Dependent on MS, some have not introduced EPR yet (UK by 2023)
EU Strategy for plastics in a circular economy (European Commission, 2018)	Vision to create circular economy by improving the whole value chain	Mixed plastic waste	More plastic waste may be diverted to recycling, so less for recovery	Medium (negative)	

Table 14: Summary of key policies that impact the selected pathways (continued)

Policy name (*voluntary initiatives)	Summary of policy	Waste stream(s) affected	Potential impact on the pathway(s)	Impact severity	Knowledge gaps
Directive 2018/850 on landfill of waste amending Directive 1999/31/EC (European Commission, 2018)	By 2035 volume of MSW going to landfill is ≤ 10 %. Separate collection of bio-waste	MRW, mixed plastic waste and municipal biowaste	Currently ~37 % MRW and ~22 % mixed plastic waste is landfilled (Eurostat, 2020). This policy will divert more MSW feedstock away from landfill and towards the gasification pathway and it will reduce the amount of bio-waste in MSW, increasing the feedstock available for the AD pathway	Medium (positive)	
Waste Framework Directive 2008/98/EC amended by Directive 2018/851 (European Commission, 2018)	Outlines waste hierarchy. Amendments include that, from 2024 bio-waste must be either separated and recycled at source or collected separately. By weight, reuse, and recycling of MSW increased to at least 55 % by 2025, 60 % by 2030, and 65 % by 2035. Revision to propose waste reduction targets of specific streams	All waste pathways	Recovery is far down the waste hierarchy, so it is not as favoured as a general method of waste management, with more waste diverted to recycling. A review of the WFD, to be more specific to waste streams (European Commission, 2020) could potentially promote the WTF pathways	Medium (positive)	Unclear on waste streams that will be considered for review
Incineration Tax (European Commission, 2001; Marino & Pariso, 2020)	Some MSs have introduced an incineration tax to promote recycling (e.g. Belgium, Denmark)	All waste pathways	Will potentially divert waste away from EfW and possibly towards other recovery but meant to increase recycling	Medium (positive)	Lack of information on the effectiveness of this policy as it is not adopted by many countries

Table 14: Summary of key policies that impact the selected pathways (continued)

Policy name (*voluntary initiatives)	Summary of policy	Waste stream(s) affected	Potential impact on the pathway(s)	Impact severity	Knowledge gaps
Ellen MacArthur Foundation* (Ellen MacArthur Foundation, 2020)	Voluntary scheme to encourage reduction of single-use plastic and recycling targets	Mixed plastic waste	Currently over 250 business signatories across Europe. Will potentially reduce overall plastic feedstock in the value chain and divert more towards recycling	Medium (negative)	
Circular Plastics Alliance* (European Commission, 2020)	Campaign to achieve EU Plastics Strategy to recycle 10 Mt plastic on the EU market by 2025	Mixed plastic waste	Currently 266 signatories across Europe. Will potentially divert more waste to recycling	Medium (negative)	
Directive 2019/904 on the reduction of the impact of certain plastic products on the environment (European Commission, 2019)	Promote transition to Circular Economy with some single-use plastics banned from 2021 and separate collection targets for others (77 % by 2025 and 90 % by 2029); ensure that PET bottles contain at least 25 % recycled plastic by 2025 and 30 % by 2030 for all beverage bottles	Mixed plastic waste (only beverage bottles)	More plastic waste may be diverted to recycling so less for recovery	Low (negative)	
Farm to fork strategy (European Commission, 2020)	Accelerate transition to sustainable food system with recommended actions for waste reduction	Source segregated food waste fraction of municipal biowaste	Will potentially reduce feedstock available for WTF pathway. This policy supports recycling of food waste via AD for renewable energy, but support for fuel production is unclear	Unknown	Recycling of food waste via AD for renewable energy supported, but unknown about fuel production
Directive 91/271/EEC on wastewater treatment (European Commission, 1991)	Protect environment from impacts of urban wastewater discharges. Encourages recycling of sludge from wastewater treatment	Sewage sludge	Divert more waste to recycling for land application rather than for recovery	Unknown	Recovery may not be encouraged, while recycling to land application is

Table 14: Summary of key policies that impact the selected pathways (continued)

Policy name (*voluntary initiatives)	Summary of policy	Waste stream(s) affected	Potential impact on the pathway(s)	Impact severity	Knowledge gaps
Directive 86/278/ EEC on sewage sludge (European Commission, 1986)	Promote use of sewage sludge in agriculture and prevent impacts to environment	Sewage sludge	Divert more waste to recycling for land application rather than for recovery	Unknown	Policy only focuses on recycling of sludge for agriculture, so unclear on policy to support use of sludge for recovery through fuel production. The EC are evaluating this directive to ensure it is updated with the current management methods of sewage sludge (European Commission, 2021) which may provide more clarity on the positioning of the WTF pathway
Effect of policy on WTF pathways is unclear					
EoW criteria in Article 6 of Directive 2008/98/ EC (European Commission, 2008)	Defines when waste obtains the status of a product or a secondary raw material	Unknown	It will be important for waste to obtain a product status to promote economic viability of the WTF pathways. There are currently only three materials for which EoW criteria have been established	Unknown	Unclear on waste feedstocks to which EoW criteria would apply. This would be a case-by-case review by the European Commission

3.3.2 Impact on waste availability

The effect of these policies on the waste volumes of the selected feedstocks is summarised qualitatively in Table 15 to understand the possible impact on future feedstock availability for the WTF pathways.

Table 15: Impact of policy and regulation on waste volumes of the feedstocks selected

	EU Volumes Mt/a	**Current EoL fate**	**How policy/regulation could impact volumes available for WTF**
Non-recyclable mixed plastic waste (MRF and mech recycling residues)	~10	Landfill (37 %), EfW (63 %)	Multiple policies promote recycling of plastic waste, which leaves less feedstock available for the WTF pathway. There may, however, be support for recycled carbon fuels from RED II, the Fuel Maritime Initiative and SAF mandate; but these are all currently undecided
Sewage sludge	~11	Landfill (8 %), Land treatment/release into water (6 %), EfW (17 %), Incineration (11 %), Land application for agriculture or ecological improvement (58 %)	Support from RED II can promote this WTF pathway but this may face issues with competition from recycling fates which are higher up the waste hierarchy
Mixed residual waste	~222	Landfill (37 %), EfW (40 %), Incineration (4 %), Recycling and backfilling (19 %)	Policy discourages landfilling of MSW with targets by 2035 which increases availability for the WTF pathway. Policies to reduce waste volumes will, however, minimise available feedstock
Municipal biowaste (inc. food and garden waste)	~48	Composting (64 %), AD (26 %), Combined composting and AD (10 %)	While there are some policies that encourage reduction of food waste, there are also targets encouraging separation of MSW which will increase bio-waste feedstock for AD

3.3.3 Key findings and knowledge gaps

Four key findings were identified from reviewing policies that could affect the WTF pathways:

- Multiple policies encourage the diversion of plastic waste away from recovery and towards recycling. This includes the following: the Single-Use Plastic Directive 2019/904; the Packaging and Packaging Waste Directive 2018/852, the Waste Framework Directive (WFD) 2008/98/EC; the EU Strategy for Plastics in a Circular

Economy; the plastic tax and the voluntary Ellen MacArthur Foundation and Circular Plastics Alliance schemes. The relevant WTF pathways can complement recycling initiatives by accepting the plastic feedstock that cannot be recycled with current technology, such as mechanical recycling. However, as this technology evolves, or as chemical recycling technologies emerge, there may be less plastic waste available for the WTF pathway.

- Policies that encourage the reduction of waste generated would limit the availability of waste feedstock for the WTF pathways. These policies include the WFD 2008/98/EC and the Farm to Fork Strategy. These would reduce the feedstock available for recovery as well as other waste management operations, including recycling.
- There are some policies that potentially promote the feedstock available for the WTF pathways. Revision of the WFD 2008/98/EC to consider waste reduction targets for specific waste streams may promote the WTF pathways although it is unclear what waste streams will be affected. Introduction of an incineration tax in all MSs would discourage EfW plants and may divert more waste towards these WTF pathways, but there would be competition with recycling to access the feedstock. The Landfill Directive 2018/850 could have a positive impact on promoting the WTF pathways by increasing the availability of MSW for recovery and reducing the amount of bio-waste in MSW, resulting in a greater volume of municipal biowaste.
- There are some policies that potentially promote the demand for fuel produced via the WTF pathways. RED II provides a strong driver for fuels derived from sewage sludge, the biogenic fraction of mixed waste, and food and garden waste. For mixed plastics and the non-biogenic fraction of mixed waste, the support is not yet clear. Criteria for recycled carbon fuels (RCFs) are under review and depending on the outcome, it may encourage MSs to utilise fuels produced from non-renewable origin to contribute to their renewable transport targets. In the UK, amendments to the RTFO were proposed recently (subject to consultation), including the definition of RCFs, which implies that the fossil fraction of MSW will be eligible for credits provided GHG savings of 50 % are reached, but pure fossil streams such as non-recyclable mixed plastic waste will not be eligible. The exact level of support for these potentially eligible RCFs is still to be decided (DfT *Targeting net zero – Next steps for the Renewable Transport Fuels Obligation).* In response to RED II and the FQD, all MSs will implement legislation to support the biogenic pathways, and to support the RCFs if they wish to. Further support for these pathways may be provided by the Fuel EU Maritime Initiative, SAF mandate, and the Sustainable Finance Taxonomy, but this remains uncertain until regulation is finalised.

The key knowledge gaps that were identified in this section and that need to be addressed are:

- There are certain policies that are not yet defined and still under review, which raises uncertainty over the availability and demand for the waste feedstocks in the WTF pathways. The feedstocks may be eligible for support under RED II and the Sustainable Finance Taxonomy, providing economic incentive to fuel producers. The Fuel Maritime Initiative and the SAF mandate may also promote the use of the waste streams in the marine and aviation industries. Greater exposure to the current status of these policies may assist with navigating the potential future impacts to the WTF pathways.
- There are some policies for which it remains unclear how they would impact the WTF pathways. Further primary research with relevant stakeholders may help to provide clarity for policies including the Farm to Fork Strategy, EoW, as well as those listed in the previous knowledge gap.

3.4 SUSTAINABILITY

To assess the sustainability impacts of the WTF pathways, first the concept of the waste hierarchy was reviewed to understand the positioning of the pathways compared to alternative EoL fates. This review also considered factors that may affect the position in the waste hierarchy, in terms of feedstock end-use. The following section then explains a methodology that can be used to evaluate the GHG impacts of the WTF pathways against different EoL fates for the waste feedstocks selected.

3.4.1 Waste hierarchy

The waste hierarchy is defined under Article 4 of the WFD 2008/98/EC as a mechanism for MSs to prioritise waste management options to achieve the best environmental outcome. The ranking of these waste management options is presented in Figure 2.

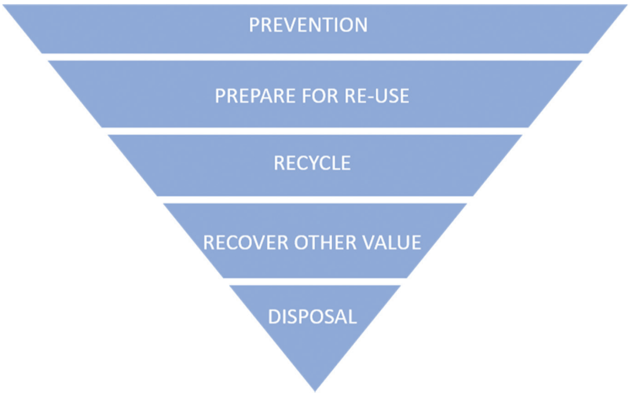


Figure 2: Stages of the waste hierarchy (adapted from the WFD EU Directive 2008/98/EC on waste)

Prevention is at the top of the waste hierarchy because this level describes the situation before material becomes waste. This allows for the following to be reduced: the quantity of waste; the environmental and human health impacts from generated waste, and the content of harmful substances in materials.

If the waste cannot be prevented, then the next option is to **prepare for reuse** so that the waste can be converted to products again. This stage can involve cleaning, repairing, and refurbishing to achieve a suitable product. This waste management option is not applicable to the sewage sludge waste feedstock.

For waste that cannot be prepared for reuse, the next ideal option would be to **recycle**. During this process, the waste is converted into products, either for the original, or other, purposes. Reprocessing of materials for use as fuels or for backfilling operations and energy recovery operations are not included in this category.

For waste that cannot be recycled, **recover other value** is the next option. The waste is prepared for a particular function, or the waste replaces materials that would otherwise have served a particular function. Recovery operations include the use of waste for: fuel or other means to generate energy; solvent regeneration; recycling or reclamation of metals and metal compounds, and oil re-refining, with the remaining recovery operations listed in Annex II of Directive 2008/98/EC.

The final stage of the waste hierarchy, and the one that should be avoided if possible, is **disposal**. Annex I of Directive 2008/98/EC lists the disposal operations, which include: landfill; deep injection into wells; incineration on land, and permanent storage in mines, for example.

Leakage of waste into the environment is an additional fate that should also be mentioned, but this would be the least desirable outcome.

The WFD (2008/98/EC) does acknowledge that following the waste hierarchy exclusively may not always result in the best environmental outcome. For example, the process to recover value from the waste of a particular waste stream may have a greater impact on the environment than disposal would have done (e.g. landfilling). To address this, the directive requires MSs to consider the overall impacts of the waste generation and management by taking a life cycle approach to justify deviating away from the waste hierarchy. Local impacts, collection systems, waste composition and quality, and the end-use of the waste-derived products, are all examples of factors that should be considered.

Within the waste hierarchy, the WTF pathways would be classed under the **recover other value** tier because the waste feedstocks are being used for fuel production.

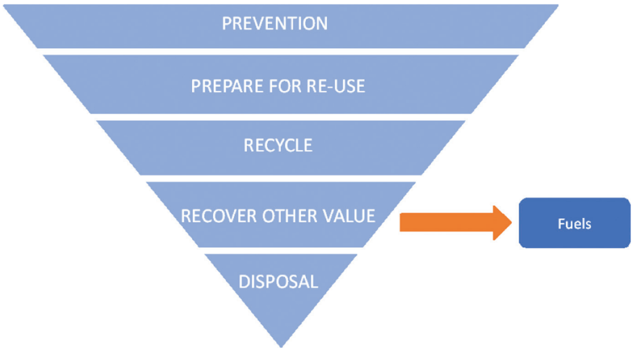


Figure 3: Position of the WTF pathways within the waste hierarchy

There are various policies and targets detailed in 3.3 that aim to reduce and recycle waste as priority actions. If the waste can be used higher up the waste hierarchy, then this would be favoured over recovery. Many of the policies and targets reviewed in 3.3 aim to reduce waste and achieve a circular economy, emphasising the importance of the waste hierarchy. For example, EPR schemes can encourage design improvements to make products more suitable for recycling and reduce the amount of waste generated during production.

If the waste was converted into a product that could be used as a chemical feedstock for example, then this WTF stream could be considered further up the waste hierarchy under recycling, compared to if the end-use of the product was for fuel production. However, there is uncertainty surrounding the definition of chemical recycling. In Europe, chemical recycling excludes the conversion of plastic waste to products that are used as fuels or as means to generate energy. Conversely, in other regions such as North America, conversion of plastic waste to products that are used as fuels is included in the definition for chemical recycling (*10 questions and answers to better understand chemical recycling*).

Sewage sludge waste used to treat land to benefit agriculture, or for ecological improvement, is considered as recycling (*Disposal and recycling routes for sewage sludge*). Directing the sludge to fuel production instead would change the position to lower down in the waste hierarchy. In contrast, sewage sludge is considered as a feedstock in Annex IX Part A of RED II for advanced biofuels production, which promotes sending sludge to recovery. This raises questions over the correct practice that should be followed when there is ambiguity between the WFD and RED II. The lack of coherency between the WFD and RED II causes confusion over how the WTF pathways would be prioritised in comparison to alternative waste management options that may result in a better environmental outcome.

Under certain circumstances, AD of food waste may count towards recycling targets if the overall environmental outcome is better than recycling that waste. The different types of waste feedstocks may have variations of the waste hierarchy. The food waste hierarchy published by WRAP in Figure 4 ranks AD as recycling, above composting. This suggests that converting food waste to fuels via AD is more favourable than composting and other recovery methods, e.g. EfW.

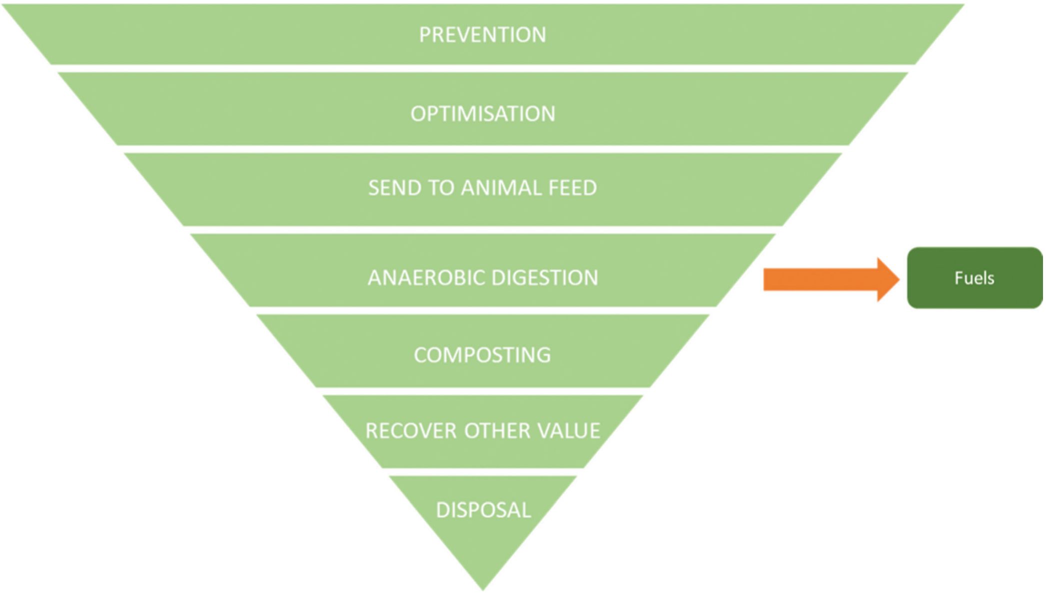


Figure 4: Stages of the food waste hierarchy, adapted from (WRAP, 2018)

However, in the WFD, AD is ranked below recycling as a form of recovering other value. Directive 2018/851 amended the WFD, and states that '*the input to the aerobic or anaerobic treatment may be counted as recycling where that treatment generates compost or digestate which, following any further necessary reprocessing is used as a recycled product, material or substance for land treatment resulting in benefit to agriculture or ecological improvement*.' The conversion of food waste to bio-crude via AD for fuel production would therefore require the digestate by-product to be used for land application purposes in order to correspond to recycling. Ultimately, the end-use of the waste determines the position of the WTF process in the hierarchy. For those pathways that generate multiple products, the end-uses may differ, which could impact the position of the WTF pathway in the hierarchy. For example, WTF pathways may produce mainly fuels, but may also produce chemical products. A material flow-tracking mechanism could be applied to evaluate the output flows on a mass balance basis, for example. This could allow for the evaluation of how much of the feedstock is used to produce fuels vs other products, and thereby give a view on where the WTF pathway could sit in the hierarchy. However, there is currently no widely accepted method to track such material flows.

3.4.2 EoL fate and GHG impact

A variety of feedstocks has been assessed in this study, which can be categorised into three types of waste: biogenic (municipal biowaste and sewage sludge); fossil (mixed plastic waste), and a mixture of the two (MRW). These different waste types will be treated differently when accounting for GHG emissions.

The biogenic feedstocks would follow the RED II GHG methodology wherein the GHG emission savings criteria have a threshold of at least 65 % emission savings for biofuels production with respect to a fossil fuel comparator of 94 gCO2e/MJ. There are no emissions associated with fuel use (i.e. zero tank-to-wheel emissions) for biofuels. The total GHG emissions are therefore driven by the well-to-tank emissions and include processing, transport and distribution, and negative emissions from any carbon capture that has not already been accounted for.

However, calculating the GHG impact of the fossil portion of these waste streams is more complex because the methodology is currently undecided. At the time of writing this report, the RED II Delegated Act detailing the methodology to calculate the GHG emission savings threshold from RCF is currently under review. In the absence of a defined approach, this study has reviewed a variety of methods which have been developed to account for fossil emissions from waste feedstocks. These methods take a life cycle assessment (LCA) approach to comprehensively assess the GHG impacts of WTF pathways, but differ in terms of the position of the system boundary and whether alternative uses of the feedstock are considered. The process flows in Figures 5 and 6 illustrate the differences between where the system boundary is drawn.

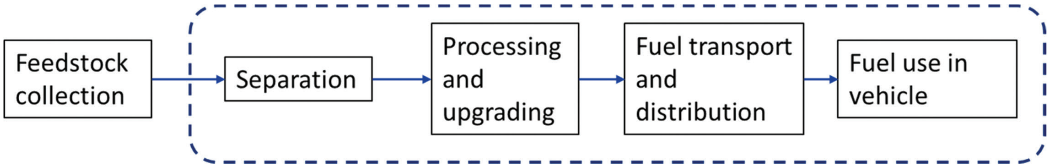


Figure 5: System boundary after feedstock collection

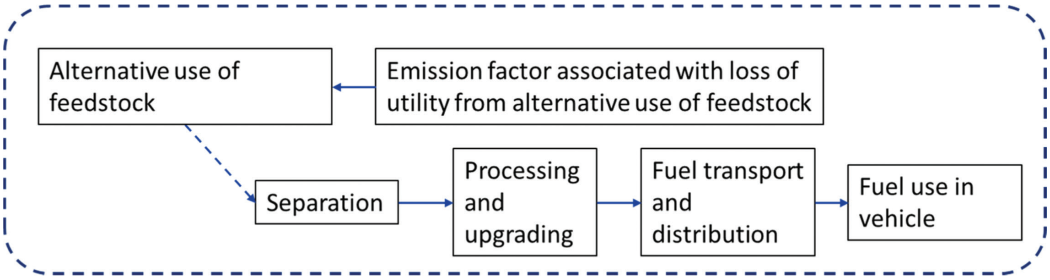


Figure 6: System boundary includes counterfactual use of feedstock

Examples of methods that have been developed to account for the fossil emissions from waste feedstocks are given in Table 16. These approaches are based on a review of the following existing methodologies: the California Air Resources Board (*Avoided life cycle GHG emissions from MSW disposal*), Benavides (*Life cycle analysis of fuels from post-use non-recycled plastics*), the JRC 2016, and the DfT methodology for biofuels and renewable fuels from non-biological origin (RFNBOs). The system boundary of these methods is identified in the table as blue for 'system boundary starts after feedstock collection' or white for 'system boundary includes counterfactual use of the feedstock'.

Table 16: GHG accounting methods for waste to fuel pathways

GHG emissions – accounting method for waste-derived fuels	Description	Advantages	Disadvantages
GHG feedstock related burden always assigned to transport fuel (system boundary starts after feedstock collection)	– Initial feedstock use did not account for CO_2 emitted to the atmosphere through fuel production and use so the fuel must account for this	– Simple to implement in practice – Fully accounts for fossil emissions from fuel production and use – Consistent with method for non-waste fossil fuels	– Not reflecting the overall GHG impact as it always implies net carbon emissions even in cases where there are none (e.g. biowaste as feedstock) – Gives same emissions in the case that carbon is recycled and in the case that carbon is additionally released into the atmosphere – No insight into which feedstock would be the best use of resources
GHG feedstock related burden assigned to transport fuel only if that carbon would not otherwise have been emitted to atmosphere (system boundary starts after feedstock collection)	– Fuel accounts for emissions that are additional to those that would have occurred anyway	– Reflects additional emissions from fuels derived from waste/by-product fossil feedstock. – No emissions assigned to carbon that would have been released anyway. This is the same principle as under the RFNBO method	– Uncertainty in assessment of whether carbon 'would have been' emitted to the atmosphere. There are different EoL fates to consider. Some of these EoL fates may sequester carbon whereas others may not, therefore it is hard to determine if carbon would have been emitted anyway. – Risk that even if carbon would have been emitted to the atmosphere it was not accounted for in the original production system, leading to some emissions not being accounted for overall

Table 16: GHG accounting methods for waste to fuel pathways (continued)

GHG emissions – accounting method for waste-derived fuels	Description	Advantages	Disadvantages
GHG feedstock related burden never assigned to transport fuel (system boundary starts after feedstock collection)	– The material (feedstock) is a waste of another process where the related GHG emissions have been already associated with the valuable products. Therefore, it is assumed that transport fuel should not account for these emissions to avoid potential double counting	– Simple to implement in practice	– Additional fossil emissions caused by production of fuels from feedstocks where carbon was previously sequestered are not accounted for – Risk that even if carbon would have been emitted to the atmosphere it was not accounted for in the original production system, leading to some emissions not accounted for overall
Counterfactual (system boundary includes counterfactual use of the feedstock)	– Fuel accounts for carbon that would not have been released to the atmosphere in alternative use scenario	– Includes indirect GHG emissions so net emissions to the atmosphere are accounted for – It has the potential to reflect the real effect when the counterfactual use of the feedstock and the utility that it replaces are known	– It may require a scenario analysis to explore the counterfactual use of a feedstock (uncertainty about what this would have been or the alternative source that will replace a lost utility). There may be disagreement on the counterfactual use when there are multiple options that could also change in the future (e.g. EfW with CCS), therefore a single assessment may not be very accurate or realistic, and hard to administer – Indirect GHGs are not included in the fuel emissions factor for biofuels treatment under the RTFO

For this study, taking a counterfactual LCA approach was considered further because it allows for the WTF pathways to be realised as potentially beneficial waste management options, compared to the current EoL fates of the waste feedstocks in question. More detail on an example counterfactual methodology is given here; however, there is no defined EU-wide method and as already highlighted in Table 16, there are other methods that have been developed and can be considered when assessing the fossil fraction of WTF pathways.

As part of a previous study for the DfT, an LCA methodology was developed and can be applied as an example of using a counterfactual LCA approach for this study. This methodology has been used by the DfT in the recently published *Targeting net zero* consultation proposing amendments to the UK's RTFO. Note that this is just an example of a potential methodology that could be followed to evaluate the GHG savings of the WTF pathways, and will not necessarily be used by the EU or individual MS.

Under this methodology, the GHG impacts of using the wastes selected in this study for fuel production will change depending on the current EoL fate from which it is diverted away. Diverting waste to a different EoL fate, such as fuel production, will generate emissions through processing and combustion, but it will avoid those emissions associated with the previous EoL fate. Some EoL fates may have generated electricity and/or heat, and so this would now be generated from a different source, meaning that the emissions associated with this replacement source also need to be considered. The previous EoL fate, in other words where the waste would have gone, can also be referred to as counterfactual. Figure 7 explains this counterfactual LCA approach to calculating the GHG emissions of WTF production.

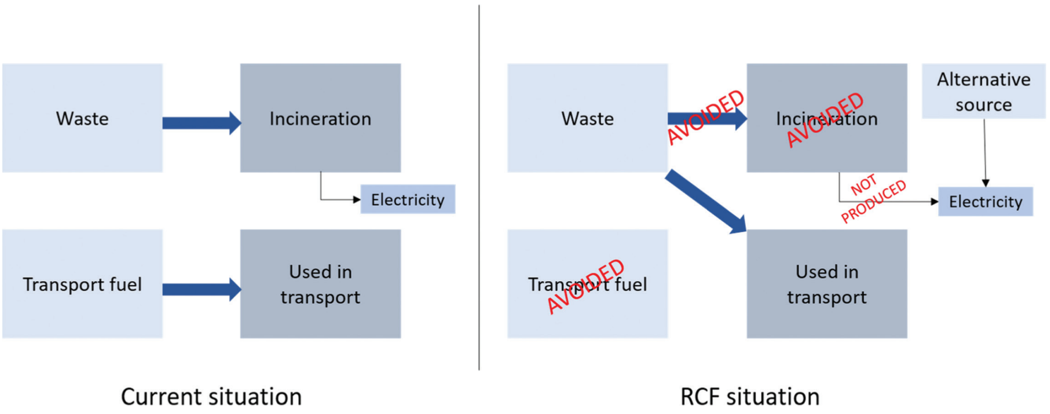


Figure 7: Schematic of counterfactual LCA concept, adapted from DfT study (*Review of technologies for gasification*)

In this method, the GHG emissions from diverting the waste to a new EoL fate is calculated by taking the difference between the avoided emissions from the current EoL fate and the production emissions from the RCFs. The fuel production emissions will include the emissions from replacing any electricity and heat, and emissions from production and combustion of RCFs. The total emissions, after accounting for avoided emissions, are then compared with a fossil fuel comparator. This comparator serves as a threshold to allow for the GHG impact of using waste for fuel production compared to fossil fuels, to be realised. If the total emissions are below the fossil fuel comparator threshold, it suggests that diverting waste to this new EoL fate would result in GHG savings.

For example, a large proportion of MRW is disposed of in landfill. Diverting this waste to the WTF pathway would avoid the emissions associated with landfill, but would introduce emissions released during the processing and combustion of the fuel, while also avoiding the emissions associated with processing and combustion of the original fossil fuel source. The emissions released during the processing and combustion of the fuel will depend on the waste feedstock used because the compositions differ in terms of the fossil and biogenic content. Biogenic waste degrades over time, releasing methane emissions, whereas fossil waste takes a long time to degrade, which is usually outside of GHG accounting timescales. Diverting biogenic feedstocks from landfill to the WTF pathways would avoid the methane emissions that would have been released during degradation of the waste. There are no emissions to account for in this method from degradation of fossil waste sent to landfill, therefore diverting the plastic waste and the fossil portion of MRW from landfill to the WTF pathways may result in greater GHG impacts.

However, landfilling of MRW contradicts the waste hierarchy which positions landfill as a last resort of waste management and recovery, including fuel production, situated higher up. Therefore, it can be argued that landfill is not an option that the WTF pathways should be compared against because it is a lower priority than recovery in the waste hierarchy. The WFD, along with many of the policies detailed earlier in this report, highlights the importance of the waste hierarchy, and presents waste targets based on alignment with the waste hierarchy. The WTF pathways should be compared against EoL fates that are positioned at the same level or higher in the waste hierarchy (i.e. recovery or higher).

EfW plants are an example of a waste management option that is also classed as recovery, so would be a suitable comparison to the WTF pathways in the context of the waste hierarchy. The electricity that would have been provided by the EfW plants would need to be replaced and so any emissions associated with this electricity generation would need to be included in the calculation. Renewable electricity would be an obvious replacement to minimise GHG impact, but multiple factors must be considered, such as: grid stability; development of infrastructure; security of supply; economic viability, and policy and regulation. An average GHG intensity was used for this methodology, which highlights a limitation of the study because the GHG intensity of the replacement electricity could be very different to the average, for example if a different fuel mix was used. Electricity grids are likely to decarbonise over time as well, which would change the GHG intensity of the replacement supply.

For well-to-wheel studies of WTF plants in the literature, the GHG emissions are for standalone plants without use of refinery process units. This differs from the WTF pathways in this study because the primary conversion technologies are integrated with a refining system for upgrading the fuels. Carrying out the upgrading step in a separate refinery is likely to impact the GHG emissions and may affect the results of the WTF pathways compared with the counterfactuals. This is a knowledge gap that could be considered as part of further research in this area.

3.4.3 Key findings and knowledge gaps

The key findings relating to the sustainability of the WTF pathways are:

- When considering its position in the waste hierarchy relative to recycling, the use of these feedstocks for fuels may not be seen as favourably as using these feedstocks for forms of recycling such as mechanical and chemical.
- Biogenic feedstocks follow the RED II methodology to account for the emissions related to the biogenic content, which is well established and widely accepted. However, for fossil wastes, there is currently no generally accepted method. Different methods have been developed to assess the emissions associated with the fossil

content of waste streams, which vary in terms of the system boundary and whether alternative uses of the feedstock are considered.

- A counterfactual method could be a suitable method to calculate the GHG emissions associated with producing fuels from fossil wastes. It considers the alternative EoL fate of the feedstock, including any utilities that now need to be provided from a replacement source (e.g. electricity produced from EfW plants). Taking a holistic approach with this type of methodology, it can be interesting to compare the WTF pathways in this study against the alternative EoL fates of the waste streams.
- Under a counterfactual approach, diverting certain waste feedstocks away from EfW plants and towards fuel production can result in GHG savings. This shows there is opportunity for the WTF pathways to disrupt the current EoL fates of certain waste streams.
- For feedstocks which are mainly fossil-derived, such as mixed plastic waste, landfilling may actually result in GHG savings compared to fuel production. This is because such wastes take a long time to degrade, which is usually outside of GHG accounting timescales, so there are no emissions from degradation associated with landfilling of fossil waste. However, for MRW streams with both biogenic and fossil components, the biogenic portion of mixed waste streams does degrade over time, releasing methane emissions. Therefore, directing certain waste streams with both fossil and biogenic components to landfill could result in a poorer outcome from a GHG perspective.

The key knowledge gaps that were identified in this section and that need to be addressed are:

- There is currently no defined EU-wide GHG methodology that has been agreed on to account for fossil emissions of wastes to fuels. This raises uncertainty around the reporting of the WTF pathway emissions, and how these pathways compare against alternative EoL fates.
- The counterfactual methodology presented as an example in this study only considers the GHG impact of the EoL fates and does not consider other impact factors such as water pollution, fertiliser replacement, air pollution, etc. A full LCA that includes these other impacts could be relevant to assessing the sustainability of these WTF pathways.
- Accounting for all GHG impacts, including methane emissions when wastes are sent to landfill, could have a significant impact on the results of the different EoL fates of the waste streams.
- Integration of CCS infrastructure should be considered in the GHG emissions calculation for the WTF pathways. CCS is likely to be essential to technology development for future energy systems, in particular for refineries which would benefit the WTF pathways.
- The literature provides data for standalone WTF plants which highlight limitations when extrapolating these conclusions to these WTF pathways. Further data should be sought on the GHG emissions associated with the refinery processing steps of these pathways.

3.5 CONCLUSIONS AND KEY GAPS TO ADDRESS

3.5.1 Overall conclusions

Phase 1 of this study has led to a number of key findings relating to technology and supply chain, economics and financing, policy and regulatory, and sustainability aspects of four WTF pathways:

- Mixed plastic waste and pyrolysis to pyrolysis oil and refining.
- Sewage sludge and HTL to HTL oil and refining.
- MRW and gasification to FT-wax and refining.
- Source separated food waste and AD to biogas, to bioCH4, to FT wax and refining.

From a technology and supply chain perspective, these pathways have a number of key challenges to overcome around the upgrading requirements of intermediate products into finished fuels. For some routes, particularly those that produce FT wax, the upgrading requirements are well understood; however, for those producing a pyrolysis or HTL-derived oil, further research is needed for better understanding.

Today, the proposed scale of the primary conversion steps is much smaller than typical refinery operations (e.g. a few percent of refinery crude processing capacity). Because of this, where a refinery takes the output from a single WTF plant, this might allow some latitude in terms of WTF-primary product quality and may allow refinery processing/ with only minor CAPEX, e.g. in WTF product handling and storage. If WTF plant scale increases, or if a refinery takes products from several WTF plants, then the WTF product quality requirements may become more stringent, and the refinery might have to make greater CAPEX, e.g. in WTF pre-treatment and refinery unit upgrades to allow higher levels of co-processing.

In general, the technical maturity of the individual process technologies is higher than that of the integrated pathway. Whilst some pathways, such as MRW gasification + FT are approaching technical maturity, others, such as the use of sewage sludge in HTL and hydrotreating/HCK are less well explored. The main uncertainties are (a) integration of technologies within individual WTF primary conversion facilities, (b) optimisation of primary-conversion product qualities to allow refineries to process/blend them at significant levels (e.g. 10–30 %).

In terms of the economic factors associated with these pathways, it is important to note that production costs, in particular those associated with feedstock and OPEX, are highly dependent on local- and project-specific factors. Since these pathways are using 'waste' resources, gate fees are an important consideration, and in certain circumstances may be considered as a revenue stream, rather than a cost, by project developers. This is particularly important for pathways where the feedstock provides energy for the process as well as being used to produce the fuels themselves (i.e. pyrolysis and gasification).

The policy and regulation around this area is highly complex, with a number of policies potentially supporting these pathways by creating demand for low carbon fuels, and a number of policies potentially diverting feedstock away from these pathways towards purposes such as recycling. In terms of those that create demand for fuel produced via the WTF pathways, RED II provides a strong driver for fuels derived from sewage sludge, the biogenic fraction of mixed waste, and food and garden waste. For mixed plastics and the non-biogenic fraction of mixed waste, the support is not yet clear. On the other hand, multiple policies encourage the diversion of plastic waste away from energy recovery and towards recycling, such as:

the Single-Use Plastic Directive 2019/904; the Packaging and Packaging Waste Directive 2018/852; the Waste Framework Directive 2008/98/EC, and the EU Strategy for Plastics in a Circular Economy.

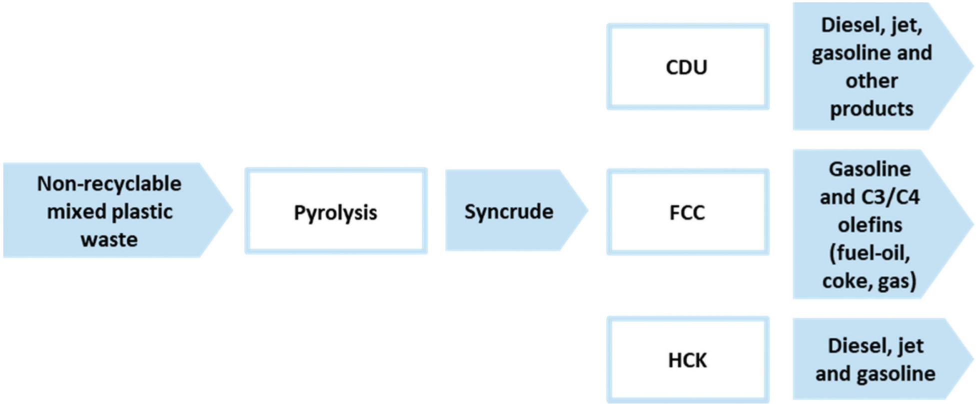
In terms of sustainability and GHG impacts, the research revealed that the RED II methodology is a suitable and universally accepted method for calculating the emissions associated with the biogenic content of the feedstocks, but there are different methods that have been developed for assessing the fossil content of WTFs. These methods have their own advantages and disadvantages, such as level of complexity, inclusion of indirect emissions, and consistency with existing principles/methods. A counterfactual LCA approach was considered in more detail because it allows the current EoL fates of the waste feedstocks in question to be compared to the use of these feedstocks to produce fuels, which subsequently allows for a system-wide understanding of the GHG impacts of these pathways. Under such a methodology, diverting certain waste feedstocks away from EfW plants and towards fuel production can result in GHG savings under certain circumstances. Results derived from this approach must, however, be viewed within the broader lens of the waste hierarchy. Whilst sending fossil waste (e.g. plastic waste) to landfill may theoretically lead to lower GHG emissions than producing and combusting fuels from it, from a waste hierarchy perspective, landfilling is not desirable. Lastly, the waste hierarchy also indicates that the use of these resources for purposes higher up the waste hierarchy than fuel production, such as recycling, is generally expected to be a more desirable purpose.

At this stage, without a detailed comparison of WTF vs WTP pathways, it is hard to give conclusive statements about the ideal role of the WTF pathways considered in this study. However, as a preliminary set of conclusions:

- When considering its position in the waste hierarchy relative to recycling, the use of these feedstocks for fuels may not be seen as favourably as using these feedstocks for forms of recycling such as mechanical and chemical. However, it should also be noted that not all wastes can be recycled, and that chemical recycling technologies have also not yet reached commercial scale. A more detailed examination in Phase 2 of the use of such feedstocks for chemical and mechanical recycling is needed to draw more specific conclusions.
- Diverting certain non-recyclable waste feedstocks away from EfW plants and towards fuel production can result in GHG savings. This shows there is opportunity for the WTF pathways to deliver GHG reductions compared to their current EoL fates.
- From a technology and supply chain perspective, these pathways may enable refinery assets to be utilised, and enable the transition towards the use of lower carbon feedstocks. However, given the relatively small volume of these wastes in comparison with the scale of refineries, whilst these pathways may enable some degree of GHG reduction, other complementary feedstocks (e.g. e-fuels) or technologies (e.g. CCS) may be needed for fuels to reach net zero emissions on a well-to-wheel basis.

3.5.2 Pathway-specific enablers and challenges

In this section, the aspects of the pathways which may help enable their deployment ('enablers'), and those aspects that make their deployment more difficult ('challenges'), are summarised by pathway.



<table>
<tr>
<td>Feedstocks
• Polyolefins are preferred for production of hydrocarbon liquids
• Polymers containing heteroatoms (O, N, S and Cl) behave differently leading to process problems (eg tars) or product impurities deleterious to further upgrading (eg acids; S- and N-compounds)
• Some polymers eg PET are more valuable if recycled separately.</td>
<td>Technical Readiness:
• TRL 8 for some polymer pyrolysis
• TRL 5/6 for low-level blending in gasoline or diesel
• TRL 4 or lower for refinery co-processing</td>
<td>Product quality
• Raw liquid includes gasoline, diesel and heavier fractions depending on feed and process design.
• The raw product is mainly paraffins, olefins and aromatics, so probably acceptable for direct fuel blending at low level. Hydrotreating may be required for higher levels in diesel.</td>
</tr>
<tr>
<td colspan="3">Process:
• Polymer pyrolysis involves thermal depolymerisation of polymers mainly to liquids; yields reported up to 85%. It is technologically distinct from biomass pyrolysis eg in terms of process design and amount of by-products (eg fuel gas and char). There are already some commercial polymer pyrolysis facilities.
• Different polymer classes (eg polyolefins; polystyrene; PET; PMMA; PVC, PU) all react differently and impact product quality, so this technology may benefit from feed segregation or separation, and feed-specific process design.
• Refinery co-processing is a an early stage of development. Pyrolysis liquid is probably olefinic so very reactive in hydrotreating units; coprocessing in refinery hydrotreaters may require low levels of feed impurities such as metals and metalloids (ppm levels), particulates, nitrogen (10-100ppm) and acidity (<1 mgKOH/g). Coprocessing in FCC units would be more tolerant of impurities, with a greater tendency to make gasoline and light olefins.</td>
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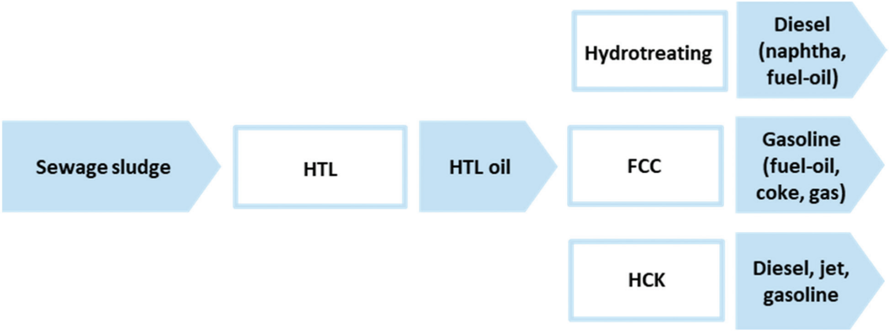
Figure 8: Flow diagram and technical summary of pathway 1 – non-recyclable mixed plastic waste

Table 17: Summary of enablers and challenges relevant to the non-recyclable mixed plastic waste pathway

Mixed plastic waste	Enablers	Challenges
Technology, supply chain and economics	– Raw waste is hydrocarbon-like which allows simple primary conversion with high yield of gasoline and diesel-range material – Primary conversion process has few steps and is technically viable at small scale; some commercial plants are already in operation – The hydrocarbons in the primary product are probably acceptable for direct blending in gasoline and diesel at low levels – Relatively easy to integrate with refined product supply-chain via hub model – Different refinery processing options might allow optimisation between gasoline, diesel, and jet (and possibly chemical feedstocks, e.g. C3=) – Where gate fees are achievable, this can have a significant positive impact on OPEX, with the waste plastic providing both the feedstock and the majority of the process energy to the pyrolysis unit	– Relatively small volume (10 Mton/year) and wide resource distribution may limit it to low-level use at individual refineries – Primary conversion, direct blending and refinery upgrading are all adversely affected by presence of oxygen-, chlorine- and nitrogen-containing polymers in waste feedstock – Primary technology is highly specific to this type of waste, little opportunity for synergy – Variability of scale/feed and applicable primary conversion technology might lead to highly variable primary products – Limited public information about refinery-based upgrading; likely hard to target a single product (especially jet) – Scalability of individual pyrolysis units is somewhat limited, meaning that economies of scale may be difficult to obtain for the primary conversion step
Policy, regulatory and sustainability	– Utilising non-recyclable mixed plastic waste may complement, rather than compete with, recycling initiatives, as mechanical recycling technologies currently are not able to process such waste	– Unclear policy positions on the use of recycled carbon fuels; there is a risk that some countries may not support fuels based on recycled carbon with no biogenic content – Certain policies (e.g. Fuel EU Maritime Initiative and SAF mandate) may promote this WTF pathway; however, these are currently under review and so potential support remains unclear – The inconsistencies between certain policies, such as RED II, and the waste hierarchy raises questions over best practices to minimise environmental impacts – EoL fates higher up the waste hierarchy (e.g. chemical recycling) may be prioritised over recovery options which include the WTF pathway



Feedstocks	**Technical Readiness:**	**Product quality**
• Sludge comprises proteins, lipids/fats and carbohydrates mixed with variable amounts of water (70-80%) and inorganics (10-40%). May need pretreatment eg to remove solids and metals. • High water content likely limits transportability leading to on-site HTL processing but centralised upgrading.	• **TRL 6/7** for wood-based HTL; lower for sludge • **TRL 4/5** for hydrotreatment of HTL oils	• Raw HTL liquid has a boiling range similar to heavy diesel, but contains % levels of oxygen; it may be acidic. • Hydrotreated product is mainly diesel-range, but the gasoline yield can be increased by hydrocracking.

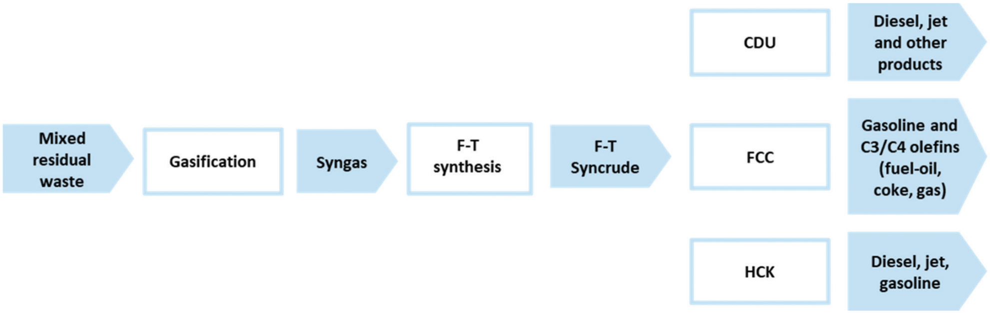
Process:

- Hydrothermal Liquefaction involves reaction of sewage sludge in the presence of high-temperature/high-pressure water, typically 200-350 Bar and 350-450 °C. It is technologically distinct from biomass Fast Pyrolysis.
- HTL technology is commercial-demo scale for treatment of woody biomass, but is also being developed for treatment of algae and wastewater/sewage sludges.
- Raw HTL products are less problematic than fast-pyrolysis oils and likely easier to upgrade, but are still unlikely to be suitable for "drop-in blending" or for co-processing in crude distillation units.
- Separate hydrotreatment and co-hydrotreatment has been tested, and likely gives acceptable products. Coprocessing in refinery hydrotreaters may require low levels of feed impurities such as metals and metalloids (ppm levels), particulates, nitrogen (10-100ppm) and acidity (<1 mgKOH/g).
- Co-processing in FCC units is likely feasible based on analogy with biomass-derived Fast-Pyrolysis Oil, and more tolerant of feed impurities than hydrotreating.

Figure 9: Flow diagram and technical summary of pathway 2 – sewage sludge

Table 18: Summary of enablers and challenges relevant to the sewage sludge pathway

Sewage sludge	Enablers	Challenges
Technology, supply chain and economics	– The primary conversion process has few steps and is technically viable at small scale – HTL plants have the potential to be more scalable than pyrolysis plants but are at an earlier technology readiness level (TRL) – Primary conversion technology is relevant to other resources, e.g. wood and algae – synergies may aid development – Relatively easy to integrate with refined product supply-chain via hub model – HTL oils contain oxygenates but these are much lower than biomass-derived pyrolysis oils – Sewage sludge can be sourced at zero, low cost or sometimes with a gate fee either providing a low-cost feedstock or a revenue driver	– Relatively small volume (10 Mton/year) and wide resource distribution may limit it to low-level use at individual refineries – Uncertain information about waste variability, e.g. source volumes and waste quality, e.g. ash; impurities from industrial waste waters – Primary product is not usable in regulated transport fuels; likely that upgrading is required at all blend levels – Limited public information about refinery-based upgrading; likely hard to target a single product (especially jet)
Policy, regulatory and sustainability	– Sewage sludge is recognised as a feedstock for advanced biofuel in RED II and there may be more support for this WTF pathway from policies currently under review that encourage uptake of sustainable fuels	– Recycling sewage sludge to land application is higher up the waste hierarchy, prioritising it over the WTF pathway – If sewage sludge was diverted to the WTF pathway, alternative fertilisers would be required for land application, which may have greater environmental impacts



Feedstocks

- Mixed residual waste is very inhomogeneous including organics which cannot be recycled (eg due to size or combination with non-recyclables) , metals, inorganics and moisture.
- Pretreatment may include screening, electric/magnetic separation, density classification

Technical Readiness:

- **TRL 5/6** for some MRW-to-syncrude facilities
- **TRL 4/5** for refinery co-processing of FT syncrude
- *(**TRL 9** for CTL and GTL production of jet and diesel, and blending with refinery products)*

Product quality

- FT syncrude is usually a mix of paraffins with a wide-boiling range and a high melting point. Likely to have low impurity levels.
- Syncrude requires cracking, preferably hydrocracking/isomerisation to produce high-quality jet and diesel. In principle, FT syncrude might be co-fed to refinery crude units at low level (eg to avoid fouling.)

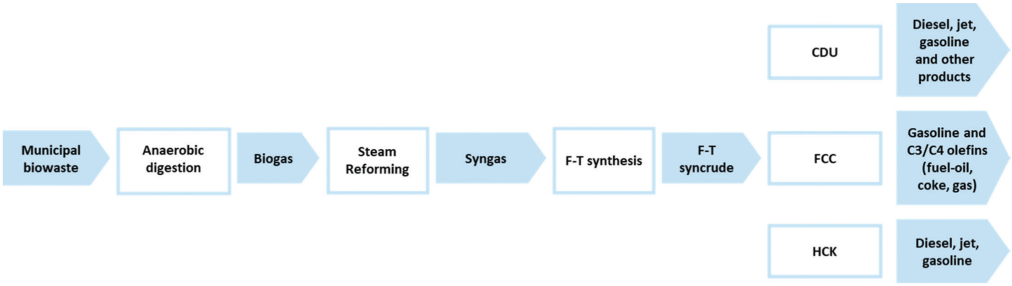
Process:

- This is a multistep process related to Gas-, Coal- or Biomass-to-Liquids, but using feed pretreatment and gasifier technology designed specifically for MRW processing eg plasma-gasification.
- GTL and CTL technologies are commercial but generally are very large scale. BTL and MRW-to-liquids facilities might be expected to be at least a factor of 10 smaller; there might be parallels with the emerging mini-GTL technologies being developed eg for oil-field flare-gas conversion.
- MRW pretreatment and gasification is commercial for production of syngas for power generation. Liquid fuel synthesis is however a more stringent application which has just reached commercial demo-scale for MRW.
- Conversion of FT syncrude to fuels is integrated with gasification in GTL/CTL today ; refinery co-processing of syncrude is less developed

Figure 10: Flow diagram and technical summary of pathway 3 – mixed residual waste

Table 19: Summary of enablers and challenges relevant to the mixed residual waste pathway

Mixed residual waste	Enablers	Challenges
Technology, supply chain and economics	– Very large waste volume (>200 Mtons/year) might enable greater synergy with refineries than smaller volume wastes – The primary conversion process utilises technologies which are already commercial in other applications – Technologies used in primary conversion are relevant to other applications – might allow synergies in development e.g. modular-FT synthesis – The economics of plants using MRW depends on receiving gate fees for waste treatment. Where available, these can provide a significant positive impact to project economics – High quality primary product with several options for refinery upgrading (e.g. HCK, FCC)	– Uncertain information about waste variability, e.g. individual source volumes and waste quality – Primary technologies are proven at different scales; challenge is integrating at common scale, and at smaller scale suited to resources – Limited public information about refinery-based upgrading; likely hard to target a single product (especially jet) – Gasifier CAPEX is significant and varies with gasifier type and scale – Gasification for downstream processing to fuels is more complex than for heat and power (e.g. impurities can deactivate the downstream FT synthesis catalyst)
Policy, regulatory and sustainability	– Landfill reduction targets will promote diversion of this waste feedstock to alternative fates including WTF – The biogenic portion of MRW is supported by RED II for fuel production – Biogenic materials degrade in landfill, releasing methane emissions, so avoiding this EoL fate and diverting waste to this WTF pathway may result in potential GHG savings	– Initiatives encouraging waste reduction limit the potential feedstock for this WTF pathway – Unclear policy positions on the use of recycled carbon fuels. The fossil content in this waste stream may affect the level of support for this pathway



Feedstocks

- Municipal biowaste is a variable mixture of food waste, "digestible" biomass and other biomass.

Technical Readiness:

- **TRL 4/5** for micro-scale FT syncrude production.
- **TRL 4/5** for refinery co-processing of FT syncrude
- *(**TRL 9** for CTL and GTL production of jet and diesel, and blending with refinery products)*

Product quality

- FT syncrude is usually a mix of paraffins with a wide-boiling range and a high melting point. Likely to have low impurity levels.
- Syncrude requires cracking, preferably hydrocracking/isomerisation to produce high-quality jet and diesel. In principle, FT syncrude might be co-fed to refinery crude units at low level (eg to avoid fouling.)

Process:

- Anaerobic digestion makes "biogas" containing similar amounts of CH4 and CO2. This could either be purified and treated as natural gas (eg GTL), or converted to syngas using developmental "tri-reforming".
- GTL and CTL technologies are commercial but generally are very large scale. Production of AD gas is smaller-scale so might require aggregation through the gas system or use of emerging micro/mini-GTL technologies (eg under development for oil-field flare-gas conversion.)
- Conversion of FT syncrude to fuels in GTL/CTLtoday is usually integrated with gasification. The AD application might benefit from aggregation of FT syncrude for centralised conversion although refinery co-processing is at an early-stage of development.

Figure 11: Flow diagram and technical summary of pathway 4 – municipal biowaste

Table 20: Summary of enablers and challenges relevant to the municipal biowaste pathway

Municipal biowaste	Enablers	Challenges
Technology, supply chain and economics	– Large waste volume (ca. 50 Mtons/year) might enable greater synergy with refineries than smaller volume wastes – The primary conversion process is built of technologies which are already commercial in other applications (e.g. AD is widely deployed) – Technologies used in primary conversion are relevant to other applications – synergies may aid development – High quality primary product with several options for refinery upgrading (e.g. HCK, FCC) – The AD producer receives a gate fee. This can become an important influence on the AD producer's economics	– Uncertain information about waste variability, e.g. individual source volumes, waste quality, methane yield – Primary technologies are proven at different scales; challenge is integrating at common scale, and at smaller scale suited to resources – Limited public information about refinery-based upgrading; likely hard to target a single product (especially jet)
Policy, regulatory and sustainability	– Policy targets to reduce the amount of biowaste ending up in MRW promote more separate collection and therefore could increase feedstock availability for this WTF pathway	– Recovery is further down the waste hierarchy compared to alternative EoL fates such as composting – Initiatives to reduce food waste will limit the feedstock available for this WTF pathway

3.5.3 Knowledge gaps and suggestions for further work

This work also highlights a number of knowledge gaps where further research is needed to better understand these pathways, and what further work could be undertaken to close these gaps, as shown in Table 21.

Table 21: Summary of the key knowledge gaps that were identified and further research required for the WTF pathways

	Key knowledge gaps	**Suggestions for further work**
Technology and supply chain	– Integration of process technologies at suitable scale for WTF facilities and implications for product quality and process operability – Impact on refinery operations if intermediate products processed at high levels (e.g. 10–30 % of refinery process feed), particularly for the waste plastic pyrolysis and sewage sludge pathways – Impact on final product quality when using higher levels of both waste-derived blend stocks and refinery products made from waste-derived feeds, particularly for the waste plastic pyrolysis and sewage sludge pathways – Scale-up of waste-derived product availability, both in terms of potential and in terms of heterogeneity of supply and management of variable waste-derived feed/ product qualities	– Primary research, including interviews with primary conversion technology developers, to better understand the plant concepts, and implications for operability, scalability, and optimisation of primary product quality for refinery blending and processing – Facilitated discussion with EI and Concawe technical experts on the technical risks and opportunities of using these intermediate products in refinery process units – Primary research with relevant experts to better understand the heterogeneity in the quality and variation of the quantity of the feedstocks in question – Regional case studies for each pathway could be carried out to understand geography-specific risks and opportunities – An in-depth examination of the supply chain of each of the four feedstocks should be carried out, to better understand the impact on the potential to scale these WTF pathways. This would include understanding current waste flows and how they might evolve over time, and challenges in accessing greater volumes of these feedstocks
Economics and financing	– Feedstock costs, policy and gate fees for these wastes are geographically dependent, significantly more so than for fossil feedstocks that are generally widely traded commodities – For CAPEX, there is limited information on the impact of different gasifier types on CAPEX and how the economics are impacted by these, the feedstock and the trade-off between syngas clean-up and FT catalyst replacement costs	– Geography-specific techno-economic modelling, combined with research on local feedstock costs and gate fees, could enable a better understanding on the economic viability of these pathways. This could help to identify locations where scale-up of these value chains could be most viable. This could also include investigating how different technology variants, e.g. gasifier types, could impact overall project economics – Techno-economic modelling would also help to better understand the circumstances under which primary conversion technologies should be co-located with the feedstock, or close to the refinery

Table 21: Summary of the key knowledge gaps that were identified and further research required for the WTF pathways (continued)

	Key knowledge gaps	Suggestions for further work
Policy and regulatory	– Several policies that could affect the pathways considered remain undefined: Recycled Carbon Fuels in RED II; the Fuel EU Maritime Initiative; the SAF mandate, and the Sustainable Finance Taxonomy – For some policies that are defined, impacts on the WTF pathways are unclear. This is the case for the Farm to Fork Strategy and EoW criteria	– Build a network/forum for EI or Concawe members to increase exposure to policy developments and better understand the implications on the WTF pathways – Further primary research with relevant stakeholders may help to provide clarity, including: the Farm to Fork Strategy; EoW criteria; RED II; Fuel EU Maritime Initiative; SAF mandate, and the Sustainable Finance Taxonomy.
Sustainability	– For wastes with both fossil and biogenic components, GHG calculations to date have not taken into account all counterfactual EoL impacts e.g. diversion of waste from EfW to products – The literature provides data for standalone WTF plants which highlight limitations when extrapolating these conclusions to these WTF pathways	– Further data should be sought on the GHG emissions associated with the refinery processing steps of these pathways – Once this is complete, conduct a counterfactual LCA assessment of the GHG impacts of these pathways, using as much pathway-specific data as possible and taking into account all counterfactual EoL impacts. This will allow for a more comprehensive understanding of the GHG impacts of these pathways, and the circumstances under which these pathways could have GHG benefits compared to the current and future EoL fates of these wastes

3.5.4 WTP pathways to explore in Phase 2

Whilst the scope of Phase 2 has not yet been clearly defined at the time of writing this report, it is worth highlighting which WTP pathways could be considered in Phase 2. It is anticipated that these WTP pathways should be somewhat comparable to those chosen for Phase 1, and therefore, it could be interesting to compare WTP and WTF pathways which utilise the same feedstock, as it may help to understand what the optimal way could be to utilise the feedstock, from a technical, economic and sustainability perspective. For now, it is assumed that the WTP pathways will focus on emerging pathways related to chemicals production, rather than more established uses which are lower down the waste hierarchy, such as EfW. A non-exhaustive list of possible WTP pathways is listed in Table 22.

Table 22: Potential WTP pathways to be considered in Phase 2

Waste resource	Primary conversion (1)	Primary product (1)	Secondary conversion (2)	Main finished products (2)
Mixed plastic waste	Pyrolysis	Pyrolysis oil	To steam cracking	Olefins, BTX
	Catalytic pyrolysis	BTX, olefins	–	–
Sewage sludge	HTL (without upgrading)	HTL oil	To steam cracking	Olefins, BTX
Mixed residual waste	Gasification + methanol synthesis	Methanol	Methanol to olefins	Olefins
			Methanol to ethanol, ethanol to ethylene	Ethylene
	Gasification	Syngas	FT to olefins	Olefins
Municipal biowaste (incl. food and garden waste)	AD	Biomethane	Oxidative coupling of methane (OCM)	Ethylene
	AD + steam reforming + methanol synthesis	Methanol	Methanol to olefins	Olefins
			Methanol to ethanol, ethanol to ethylene	Ethylene
	AD + Steam reforming	Syngas	FT to olefins	Olefins

ANNEX A
SUPPLY CHAIN – REFINERY

In 2019, EU demand for refined products was almost 1 800 kton/day, including approximately 220 kton/day of gasoline, 180 kton/day of jet and 800 kton/day of diesel plus smaller amounts of distillate heating oil and marine distillate ('gas oils') (Fuels Europe, *Statistical report*). More than 90 % was derived from crude oil, and most was manufactured in European refineries. Some of the European demand for jet and diesel was satisfied through imports; some European production of gasoline was exported.

The primary purpose of an oil refinery is to separate crude oil into appropriate boiling fractions, upgrade them to improve their properties, or convert them from low-value fractions into more valuable ones (e.g. by 'cracking' high boiling fractions into low-boiling ones). This creates a suite of blend stocks which can be combined into finished fuels. A typical finished gasoline might contain five or more blend stocks made by different processes and each with its own characteristic properties.

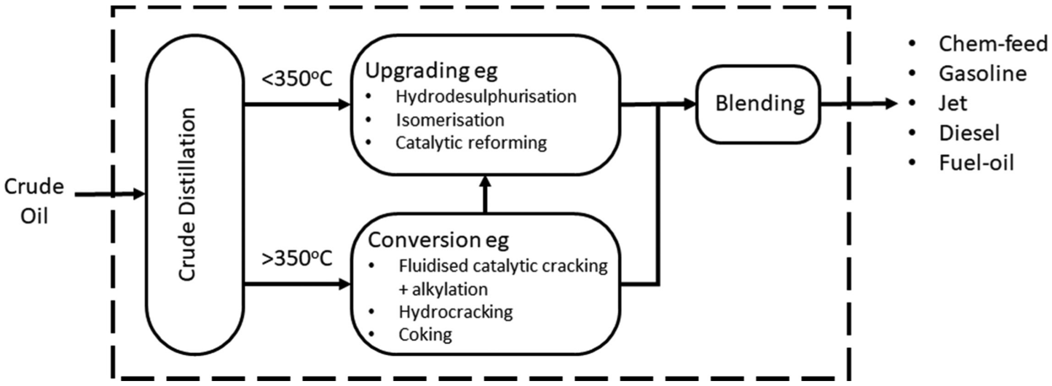


Figure A.1: Refinery supply chain

As well as crude oil, refineries may import smaller amounts of other liquid feedstocks, typically intermediates from other refineries (e.g. gas-oils and residues), natural gas condensates and petrochemical by-products (such as aromatics-plant raffinate or steam-cracker pyrolysis oils.) More recently, a few refineries have imported small amounts of bio-feedstocks such as vegetable oils or waste fats. The entry point into the refinery depends on whether the imported liquid:

- can be used directly as a blend stock for finished fuel;
- needs separation before being used as blend stock;
- needs chemical treatment before being used as a blend stock, or
- needs severe processing to change its boiling range.

These in turn depend on the characteristics of the liquid compared with (a) fuel specifications such as EN228 and EN590 for gasoline and diesel in Europe, or (b) process feedstock quality limits set by individual refineries, e.g. for hydrotreater feedstock. Impurities, corrosivity and fouling potential are important considerations, especially if adding a small amount of a co-feed might jeopardise the entire refinery operation. Note that an imported liquid used at % low level (e.g. a few % in blend) has less impact on refinery operation or finished product quality so can be allowed greater freedom than the same liquid used at higher level (e.g. several 10s of % in blend). Key issues are:

- Boiling range: some 'alternative' feeds might be presented as 'syncrudes' with a wide boiling range which spans the boiling ranges of several refined products or process feedstocks. Gasoline and diesel typically have boiling ranges of 40–180 °C and 180–360 °C respectively so anything with a wider range requires separation. This might suggest processing in a CDU, in which case the separated fractions would proceed to further processing, e.g. hydrotreatment, catalytic reforming etc. However, depending on scale, there might be other options. For example, refinery 'conversion' units such as FCC and HCK themselves make a wide boiling 'syncrude' so usually have their own fractionation units. FCC products (e.g. gasoline, diesel, fuel oil) usually need further processing, but hydrocracker products (gasoline, jet, diesel) might go directly for final product blending. The choice depends on many factors including (a) the relative amounts of crude-derived and alternative feeds; (b) the exact boiling distribution; (c) the need for any upgrading; (d) the risk of chemical interactions between the feeds, and (e) the presence of contaminants which might cause corrosion, fouling or catalyst poisoning.

  Some 'alternative' feeds might have a boiling range which is close to a normal product such as gasoline, jet, or diesel, in which case they do not require 'conversion.' They might/might not require upgrading to improve their properties. Either way, this is not the end of the story. Fuel specifications such as EN228 and EN590 also have limits on the 'shape' of the boiling curve, meaning that blend stocks have to be carefully matched.

- Bulk composition: even if the boiling range is compatible, the bulk composition of the imported liquid remains an important consideration both for refinery processing and for the performance of the finished fuel. Refinery stream are mainly hydrocarbons, e.g. paraffins, olefins, aromatics and naphthenes (cyclic non-aromatic hydrocarbons) which can have different physical properties and chemical reactivities. Bulk composition is usually not a limit for refinery processing, but it can determine which process units would be used. For example, a high olefin content can make a feed problematic because it is too reactive for many refinery processes.

  Refinery processes are designed to streams which might contain up to a few% of sulfur, but typically have very low levels of oxygen or nitrogen (e.g. < 1wt%). Co-processing a material which is high in oxygen or nitrogen might therefore cause problems. The nature of the problem depends on chemical type; for example, some oxygen compounds are acidic, but others are not. They might convert to water or carbon oxides; some refinery processes are poisoned by water, whereas others are poisoned by CO.

  Hydrocarbons generally have an energy content of 40 to 45 MJ/kg; their 'combustibility' varies considerably; aromatics perform well in spark-ignition (gasoline) engines, but badly in compression-ignition (diesel) engines. Refinery gasoline typically contains aromatics and olefins which are good for octane-rating; however, EN228 limits them to 35 % and 18 % respectively. Refinery diesel contains aromatics and paraffins. EN590 for diesel has no limits for 'aromatics' but it does have a density limit (820–845 kg/m^3) which is a proxy for ~25 % aromatics; it has an 8wt% limit for polyaromatics because of potential links to particulate emissions.

- Impurities: the fuel specifications limit composition (e.g. >10 ppm sulfur in either fuel; >1 % benzene in gasoline) and behaviour (e.g. corrosivity, colour, stability, viscosity, filterability). The latter may have links to contaminants, e.g. di-olefins raise worries about gums and fouling; phenols, acids, aldehydes/ketones affect materials' compatibility. Refiners would worry about corrosivity (e.g. 'total acid number' >1 mgKOH/g) and catalyst deactivation (e.g. >10 ppm phosphorus; >500 ppm nitrogen especially anilines and pyridines and nitriles). Silicones, metals, semi-metals (e.g. Hg, Cd or as) and fine particulates can all be processing issues at ppm levels.

Concawe's *Refinery 2050: Conceptual assessment* considered use of alternative feedstocks in four ways, which are outlined in Table A. 1.

Table A.1: Refinery use of alternative feedstocks

Approach	Detail	Limit	Recent example
Blending	The alternative material is blended with refined products to make a finished transport fuel	Limited by fuel blending properties	E.g. 7 % FAME in EN590 diesel
Co-feed	A weak mixture of alternative feed and fossil-feed is fed to an existing refinery process unit; only minor modification required	Limited by reactivity, H2-consumption, impurities, impact on product quality	E.g. perhaps up to 5 % vegetable oil might be used in existing diesel hydrotreater feed; several European refinery operations announced
Unit modification	Modifications to process unit allow a stronger mixture of alternative feed and fossil-feed to be fed to an existing refinery process unit	Limited by reactivity, H2-consumption, impurities, impact on product quality but to a lesser degree	E.g. perhaps up 30 % vegetable oil might be used in feed to modify diesel hydrotreater feed depending on its design
Unit repurposing	Major modifications allow an existing process unit to be switched to 100 % alternative feed	Many technical constraints overcome, perhaps at the expense of unit capacity	E.g. conversion of hydrotreating units for bioprocessing at ENI Porto Marghera and Total La Mede refineries

Potential 'entry points' into the refining process are:

- CDU – may be viewed as the logical entry point for an alternative feed which requires fractionation. Any restrictions or upsets would, however, have a major impact on refinery profitability – potential issues include fouling, corrosion, chemical compatibility between feeds and impact on individual product draws.
- Conversion units – such as FCC and HCK, are used to convert high boiling materials (e.g. fuel oil range) into lighter products such as gasoline, jet, and diesel. Neither is 100 % selective to a specific product, but FCC is usual viewed as 'gasoline-oriented', HCK as 'diesel-oriented'. These units usually have their own product fractionation systems.

- Naphtha hydrotreatment (NHT) and selective hydrodesulfurisation (SHDS) – these are used to desulfurise gasoline-range materials prior to further conversion or product blending. NHT removes sulfur, saturates olefins, and might remove some oxygenates; its operation is critical because the subsequent processes (catalytic reforming and isomerisation) are very sensitive to feed impurities. SHDS is usually a smaller unit specifically for desulfurisation of FCC gasoline without saturation of olefins.
- Distillate hydrotreatment (DHT) – primarily used to desulfurise diesel-range materials, with different designs for different duties. Low-pressure units are cheaper to build and run, but might only be able to desulfurise 'easy' feeds; high-pressure units are more costly but can desulfurise 'harder' feeds (such as FCC diesel) and may give other improvements (e.g. a moderate degree of aromatics saturation.) A few refineries have specialist units, e.g. for dewaxing or dearomatisation.

As reference points for the impact of alternative feed volumes, Table A. 2 shows some indicative capacities for specific refinery processes in a 'notional' 180 kbbl/day EU refinery with the same configuration as the EU aggregate. Note that some refineries may have one, two or sometimes three units of each type (based on (Concawe, 2019). For guidance, 'Co-Feed' and 'Unit Modification' are represented as 5 % and 30 % of total capacity; in reality, these values depend on the detailed properties of the crude-derived feed, the alternative feed, the unit design and to what extent it has been modified to allow co-feeding.

Table A.2: Indicative production and unit feed rates for a 'notional' 180 kbbl/day EU Refinery

	Process capacity, kton/day	Production, kton/day		
		Gasoline	Jet	Diesel and gas oils
Whole refinery	25,0	4,9	2,1	11,2
30 % of Refinery	7,5	1,5	0,6	3,4
5 % of refinery	1,3	0,2	0,1	0,6
FCC+alkylation	4,7	2,1		0,5
30 % of FCCU	1,4	0,6		0,14
5 % of FCCU	0,2	0,11		0,02
HCK	3,0		0,7	2,0
30 % of HCK	0,9		0,2	0,6
5 % of HCK	0,15		0,04	0,1
NHT	4,6	4,6		
30 % of NHT	1,4	1,4		
5 % of NHT	0,2	0,2		
DHT	7,2			7,2
30 % of DHT	2,2			2,2
5 % of DHT	0,4			0,4

ANNEX B
WASTE PATHWAYS

B.1 MIXED PLASTIC WASTE AND PYROLYSIS

B.1.1 Process

Despite the name, there is only a superficial resemblance between 'plastics pyrolysis' and 'biomass pyrolysis' which was considered in Concawe's 2050 Refining study. Plastics pyrolysis involves heating plastic waste to 400–600 °C in the absence of air, e.g. *Plastics to oil products*; *Thermal conversion of plastic-containing waste: A review*, and *Catalytic pyrolysis of plastic waste for the production of liquid fuels for engines*. There are various process concepts including auger, tubular and 'molten-pool' batch reactors through to fluidised beds where a heat-transfer medium such as sand is used to provide high-heating rates and short contact times. Some use solid 'cracking' catalysts (e.g. ZSM5) to direct product distribution and quality *Advances and approaches for chemical recycling of plastic waste*; *Upcycling polyethylene plastic waste into lubricant oils*. The liquid yield can be as high as 85 wt%, with the balance being light gases (H_2, CO, light hydrocarbons which can be used as process fuel) and solid carbonaceous char (which may contain metals and inorganics from the raw feed or the process. The liquid yield is influenced by the feedstock, reactor temperature and residence time primarily, as well as any *in situ* catalyst that may be present.

B.1.2 Feedstock

Different polymer types react differently when pyrolysed. For example, polystyrene and PMMA (Perspex) and Nylon depolymerise to monomers, whereas polyethylene and polypropylene 'crack' into mixtures of hydrocarbons. Polymers containing oxygen (e.g. polycarbonates, PET) give lower yields of hydrocarbons and may be more valuable if recycled independently; polymers containing chlorine, nitrogen and sulfur (e.g. PVC, polyurethane, nitriles) give hazardous by-products and again are best treated separately *Thermal conversion of plastic-containing waste: A review*; *Introducing plastics energy*. Plant design and conditions reflect which polymers are in the feed.

This study therefore focuses on polyolefins (HDPE, LDPE, PP) which make up the bulk of raw mixed plastic waste (WRAP) . It requires mechanical sorting/cleaning to reduce contaminants (e.g. metals, PVC, PET, PS) and shredding to facilitate handling. Depending on contaminant levels, the pyrolysis plant may still need measures to dechlorinate the final product (*Thermal conversion of plastic-containing waste: A review*).

B.1.3 Primary conversion product

Thermal cracking of polyolefins generally gives a wide molecular weight distribution in the pyrolysis product, although this may be offset by plant design or use of catalysts (Budsaereechai, Hunt, & Ngernyen, 2019). Depending on process conditions, it might be suitable for fractionation into transport fuels (e.g. 40–400 °C); heavier products (e.g. with end point >400 °C) might require further processing. Polyolefin cracking generally gives a mixture containing perhaps 1:4 aromatics:aliphatics, with higher temperatures and longer residence times favouring aromatics but reducing the liquid yield (e.g. *Plastics to energy – Fuel chemicals and sustainability implications*). The aliphatics are a mixture of paraffins and olefins, both linear and branched. The balance depends on process conditions and feed composition; PP tends to be more reactive than PE.

Information about impurity levels (e.g. residual oxygenates) and stability is sparse and likely to be case-specific, but in general, it is best to avoid plastics containing oxygen, such as PET.

Entrained char particles are an issue with some biomass pyrolysis processes and might be linked to fouling or plugging of catalytic reactors used for upgrading. Cyclonic treatment of pyrolysis vapours seems to be accepted as suitable for removal of particles >10um with R&D on liquid treatments, e.g. ceramic membrane filters for <10um (Huber, Upadhye, Ford, Bhatia & Badger, 2011). It is not clear if the same problem occurs with plastics pyrolysis; the presence of inorganic fillers might also be an issue.

B.1.4 Integration with refined product supply chain

In 2015, there were six commercial pyrolysis facilities either operating or planned (*Thermal conversion of plastic-containing waste: A review*) Table 14; (*2015 Plastics-to-fuel project developer's guide*) with others announced more recently (Table B.1.4.1). Plant capacities are reported in the range 20–60 tons/day, with potential to scale to perhaps 300 tons/day (*How plastics waste recycling could transform the chemical industry*). Some are already supplying into the refined product chain, e.g. Plastic Energy fractionates its raw pyrolysis oil into heavy fuel oil, diesel, and naphtha; (*Plastic energy plans 10 chemical recycling plants in Europe, Asia by 2021*) reports that it is supplying Repsol.

Table B.1.4.1: Commercial scale plastics pyrolysis plants, 2019 (Source: A = *(Global production of bio-methane and synthetic fuels – overview)*, B = *(Thermal conversion of plastic-containing waste: A review)*

Plant	Location	Status	Product	Production ton/day	Ref
Vadxx	Akron, USA	operational	diesel, naphtha	50	A, B
PlasticEnergy	Seville, Spain	operational	diesel, naphtha	20	A, B
PlasticEnergy	Almeria, Spain	operational	diesel, naphtha	20	A, B
PARC-1	Jiangsuu, China	operational	diesel, naphtha	10	A
PARC-2	Jiangsuu, China	operational	syncrude	15	A
MK Aromatics	India	operational	syncrude	10	A
Pyrocrat	India	operational	pyrolysis oil	90	A
Suez SITA	UK	operational	diesel	20	A, B
IGE	Australia	idle	diesel, naphtha	100	A
Cynar	Ireland	idle	diesel, naphtha	10	A
Renewology	Nova Scotia, Canada	planned	diesel	10	A
Quantafuel	Skive, Denmark	under construction	mainly diesel	50	A
Quantafuel	Frederikstad, Denmark	planned	mainly diesel	50	A
Quantafuel	Netherlands	planned	diesel, naphtha	250	A
RES Polyflow	Indiana	planned	diesel, naphtha	unclear	A, B

Table B.1.4.1: Commercial scale plastics pyrolysis plants, 2019 (Source: A = *(Global production of bio-methane and synthetic fuels – overview)*, B = *(Thermal conversion of plastic-containing waste: A review)* (continued)

Plant	Location	Status	Product	Production ton/day	Ref
IGE	Amsterdam	under construction	marine diesel	100	A
IGE-1	UK	planned	n/a	200	A
IGE-2	UK	planned	n/a	200	A
IGE-3	UK	planned	n/a	200	A
IGE	Indiana	planned	n/a	1 500	A
ReNew	Teesside, UK	planned	n/a	50	A
Valoriza	Jerez, Spain	planned	n/a	150	A

In contrast, a notional EU refinery would make several thousand tons/day of gasoline or diesel, so a single pyrolysis plant would be unlikely to supply more than 5–10 % of total fuel product. This suggests a 'hub' model where several pyrolysis plants supply oil to a single refinery.

Most of the current plants make products for fuel blending (*Thermal conversion of plastic-containing waste: A review*; *Plastics: Towards a circular economy*), so the quality of pyrolysis products is acceptable for low level blending; all that may be required is fractionation into the right boiling range. The olefinicity (*Thermal conversion of plastic-containing waste: A review*; *Alternative diesel from waste plastics*) might pose a fouling risk for conventional distillation.

At higher blend levels, some properties might need closer scrutiny:

- The gasoline fraction may well be acceptable as regards bulk composition and properties – it resembles refinery gasoline in terms of hydrocarbon types and its octane rating is good, 85–95 RON (*Production of liquid fuel from plastic waste using integrated pyrolysis method with refinery distillation bubble cap plate column*). Subject to impurities such as metals, nitrogen, oxygen, the main concerns would likely be sulfur and di-olefins. In principle, these could be resolved by hydrotreatment in the NHT (reformer pretreat) or SHDS (FCC gasoline post-treat); the latter might be preferred in order to maintain octane rating. Very high benzene content (e.g. >10 %) might be an issue, unless this could be diverted to chemical use.
- The diesel fraction might be more problematic. Its bulk properties (aromatics content; olefin content as indicated by 'Bromine Number;' (*Alternative diesel from waste plastics*)) suggest it may resemble refinery cooker gas-oil, which is not suitable for high level blending in diesel. High olefinicity is not an issue in itself, but it might indicate poor stability, e.g. to polymerisation and gum formation during transport and storage. In principle, this might be treatable with antioxidant additives, but it depends on how long the product needs to be stored for. If, however, the product requires hydrotreatment to remove sulfur then the olefin content would need care. Not all refineries have hydrotreaters suitable for handling cooker gas-oils; those that do might have a limit of perhaps 10–20 % in hydrotreater feed, say 500 to 1 000 ton/day for a mid-size unit.

Heavy pyrolysis oil, with content boiling >360 °C, would likely be acceptable as either FCC or HCK feed. The FCC process would likely crack the aliphatic material mainly to light-olefins (C3=, C4=) and gasoline, but might also give some fuel-oil and coke. HCK would likely give higher liquids' yield with the split gasoline:diesel depending on process type/conditions. HCK is a high-margin unit with stringent requirements for feed impurities (poisons, particulates); FCC would be significantly more tolerant to feed quality. Both units typically operate at 3 000 to 5 000 tons/day.

The yields and qualities from refinery processes depend on the properties of the raw oil, which in turn depends on the design of the pyrolyser. It is not possible to do more than generalise at this stage.

B.2 SEWAGE SLUDGE AND HYDROTHERMAL LIQUEFACTION

B.2.1 Process

Pyrolysis (B.1.1) is a purely thermal process, whereas HTL uses a combination of temperature and the reactivity of high-pressure/high-temperature liquid water. There are significant differences in plant design and process chemistry. Pyrolysis is best suited to dry feedstocks, but HTL can use wet feeds, so attention has been focused in three areas: wet/green biomass; algae, and water-treatment sludges.

There are variations in HTL design addressing both engineering and feedstock issues (*Advancement of hydrofaction technology platform*; *Fundamentals of Hydrofaction™: Renewable crude oil from woody biomass*, and *Conceptual biorefinery design and research targeted for 2022: Hydrothermal liquefaction processing of wet waste to fuels*), but overall the process comprises:

- Pre-treatment to remove gross contaminants and adjust the feed slurry to 20–30 %.
- Pressurisation/preheat typically using a screw-feeder and fired pre-heat.
- HTL reactor: typically, 200–350 Bar and 350–450 °C, residence time = 10s of minutes. Some versions use a water-soluble catalyst (*Fundamentals of Hydrofaction™: Renewable crude oil from woody biomass*).
- Product separation – representative yields are ~45 % HTL oil, ~30 % aqueous phase, ~15 % gas, ~10 % solids.

Depending on feed quality, the oil phase may require deashing, dehydration and desalting before use or further upgrading. The aqueous phase contains soluble by-products (mainly oxygenates) so is treated and recycled. The off-gas is mainly CO_2 with some C1-C5 hydrocarbons so provides some process energy. The ash contains residual hydrocarbons and inorganic impurities from the feed.

B.2.2 Feedstock

Most HTL development has focused on biomass and algae (*Hydrothermal liquefaction of biomass: Developments from batch to continuous process*; *Advancement of hydrofaction technology platform*; *Co-processing potential of HTL bio-crude at petroleum refineries – Part 1: Fractional distillation and characterization*; *Co-processing potential of HTL bio-crude at petroleum refineries. Part 2: A parametric hydrotreating study*; *Hydrothermal liquefaction of macroalgae for the production of renewable biofuels*, and *A review on hydrothermal liquefaction of biomass*) with wastewater-treatment sludge being thought to resemble the algae application (*Conceptual biorefinery design and research targeted for 2022: Hydrothermal liquefaction processing of wet waste to fuels*). Wastewater-treatment-sludge is composed of: water; proteins; lipids/fats; carbohydrates, and inorganic ash and grit. Its composition depends on the type of treatment plant, the sources of the wastewater/sewage, the weather and other factors. Ash content is viewed as the most variable parameter – 10 to 40 %. Sludge also appears to contain % levels of nitrogen, phosphorus, and sulfur which raises questions about the carry-over into the HTL-oil.

B.2.3 Primary conversion product

Again, care must be taken to distinguish between HTL oils and oils from thermal processing, such as fast-pyrolysis bio-oils. Biomass pyrolysis oil has a reputation for being an acidic, unstable emulsion, which is due in part to the high oxygen content of its organic components. HTL oil has a much lower oxygen content – 5–10 wt% compared with 40–50 % for thermal pyrolysis oil (Table B.2.3. 1) and is generally considered easier to handle. However, it differs considerably from fossil hydrocarbon oils, being a complex mixture of hydrocarbons; fatty acids; amides; ketones; phenols; alcohols, etc. (*Conceptual biorefinery design and research targeted for 2022: Hydrothermal liquefaction processing of wet waste to fuels*). There is also some uncertainty about its properties, particularly acidity (Table B.2.3. 1). Reports, mainly about lab-scale work on algae (*Hydrothermal liquefaction of macroalgae for the production of renewable biofuels*, *A review on hydrothermal liquefaction of biomass*), describe HTL oils with complex composition, high acidity and poor storage stability. The boiling profile is quite broad, with perhaps ~25 % boiling above 400 °C (*Advancement of hydrofaction technology platform*, and *Conceptual biorefinery design and research targeted for 2022: Hydrothermal liquefaction processing of wet waste to fuels*). This product probably needs dedicated logistics and storage.

Table B.2.3.1: HTL-oil composition

Reference	Feed	C wt%	H wt%	O wt%	N wt%	S wt%	P wt%	Acidity (mgKOH/g)
Conceptual biorefinery design and research targeted for 2022: Hydrothermal liquefaction processing of wet waste to fuels	Sludge	79	11	5	5	1	n/a	n/a
Fundamentals of Hydrofaction™: renewable crude oil from woody biomass	Wood	81	9	10	0	0	n/a	9
Conversion of a wet waste feedstock to biocrude by hydrothermal processing in a continuous-flow reactor: grape pomace	Pomace	80	10	7	2	0	n/a	61
Conversion of a wet waste feedstock to biocrude by hydrothermal processing in a continuous-flow reactor: grape pomace	Pomace	82	10	6	2	0	n/a	70

B.2.4 Integration with refined product supply chain

Several studies have investigated hydrotreatment to improve the properties of HTL oils either using dedicated units or as co-feeds to refinery units (*Co-processing potential of HTL bio-crude at petroleum refineries – Part 1: Fractional distillation and characterization*; *Co-processing potential of HTL bio-crude at petroleum refineries. Part 2: A parametric hydrotreating study*; *Conceptual biorefinery design and research targeted for 2022: Hydrothermal liquefaction processing of wet waste to fuels*; *Hydroprocessing of bio-crude from continuous hydrothermal liquefaction of microalga*; *Co-processing of hydrothermal liquefaction biocrude with vacuum gas oil through hydrotreating and hydrocracking to produce low-carbon fuels*, and

Co-hydroprocessing HTL biocrude from waste biomass with bitumen-derived vacuum gas oil). Approaches include:

- Conventional hydrotreatment without conversion – gives roughly 1:4 gasoline: diesel; the diesel fraction retains material boiling above 360 °C so might be aimed at marine diesel rather than road diesel.
- HCK – gives roughly 3:1 gasoline: diesel.

The treated products are mainly paraffinic containing 5–15 % aromatics. Aromatic content generally increases with boiling point, so the gasoline is probably relatively low octane; the diesel quality is probably quite good. The sulfur content is typically a few 10s of ppm. Information on other impurity levels is scant – oxygen content is <0,1 wt% or not reported, with little information on acidity, stability, or materials' compatibility.

Studies (*Conceptual biorefinery design and research targeted for 2022: Hydrothermal liquefaction processing of wet waste to fuels*) assume that sludge processing would be co-located with the water-treatment plant in order to avoid transport of wet sludge. PNNL's design basis is 100 ton/day of sludge (dry basis) for a 110 million gallon/day wastewater treatment plant, noting that US treatment plants vary in size from <1 to 950 million gallons/day. The reference HTL plant makes ~10 ton/day of HTL oil, so PNNL has assessed 10 local HTL plants feeding plus a centralised ~100 ton/day hydrotreating facility. The reference hydrocracker has a capacity of 2 600 ton/day of feed and makes ~2 000 ton/day of diesel; i.e. sewage-derived HTL-oil from 10 reference-scale plants would represent ~5 % of feed.

There is little information about co-feeding raw-HTL oil to refinery hydrotreating/HCK plants. The oxygen content leads to high hydrogen consumption (~5 kgH_2 per 100 kg-HTL oil), which combined with high upper boiling-point and high nitrogen content suggest that conventional diesel hydrotreatment units would not be suitable. High acidity (e.g. TAN greater than a few mgKOH/g-oil) would require pre-treatment which might be 'stabilisation hydrotreatment' as suggested for biomass fast-pyrolysis oils, or something less severe. Other contaminants in the raw HTL-oil (e.g. halides, sulfur, metals, particulates) would also need to be removed before hydrotreatment to avoid fouling and catalyst deactivation. Research papers (*Co-processing of hydrothermal liquefaction biocrude with vacuum gas oil through hydrotreating and hydrocracking to produce low-carbon fuels* and *Co-hydroprocessing HTL biocrude from waste biomass with bitumen-derived vacuum gas oil*) have investigated co-hydrotreatment of 10–15 % HTL-oil with crude-derived vacuum gas oil (VGO, boiling range perhaps 360–500 °C). Issues included catalyst deactivation. Fluid-catalytic cracking is more suited to low-quality vacuum gas-oil (VGO)-range feeds, so has been tested with 10 % HTL-oil co-feed (*Co-processing of hydrothermal liquefaction algal bio-oil and petroleum feedstock to fuel-like hydrocarbons via fluid catalytic cracking*). Again, HTL-oil seems to have affected catalyst activity.

Commercial experience of HTL mainly concerns wood not sewage sludge:

- Steeper Energy has operated a 30 kg/hr pilot-unit and has plans for wood-to-marine fuel plant in Norway (*Advancement of hydrofaction technology platform*). There is a more recent announcement regarding a sewage-sludge treatment in Calgary, Canada (*Memorandum of understanding (MOU) signed by the city of Calgary with Steeper Energy Canada Ltd.*). Biofuels Digest (*First oil produced at 1/2 barrel-per-day hydrofaction pilot plant*) reported that Steeper was planning 50 000 to 1 00 000 metric ton wood-to-marine fuel facility at the port of Frederikshavn. If this is dry-wood basis, then it might translate to 20 to 50 ktons/year of liquid-hydrocarbons.
- Licella has a demonstration wood-to-HTL unit operating at 10 000 'slurry tonnes per annum', perhaps 500 to 1 000 kton/year of liquid hydrocarbons. Canfor-Licella

(*Canfor eyes Prince George for major biofuel facility* and *Licella has the world's only large scale hydrothermal upgrading plant, located on the NSW Central Coast in Australia*) suggests that a new facility processing wood-pulp could produce up to 4 00 000 barrels of biocrude annually (~50 kton/yr).

B.3 MIXED RESIDUAL WASTE

B.3.1 Process

Conversion of MRW to synthetic refinery feedstocks or fuels has two major steps: (a) gasification of MRW to synthesis gas, and (b) conversion of synthesis gas into products.

Gasification

Gasification is an established thermochemical process in which carbonaceous feeds such as coal, residual oil, biomass, or biogenic wastes are converted into synthesis gas ('syngas') – a mixture containing mainly hydrogen and carbon monoxide. It is used to make syngas both for combustion/power-generation and for synthesis of chemicals and transport fuels (e.g. H_2, methanol, ammonia, FT products). Synthesis reactions usually require a pure syngas which is richer in hydrogen, so plants include syngas cleaning and a follow-on catalytic 'shift-reactor' or additional green hydrogen input to adjust the CO/H_2 ratio. The process requires oxygen or air, sometimes supplemented by steam, which enhances shift in the gas phase. The heat needed for gasification is usually provided by combustion of some feedstock within the gasifier or by external combustion of unwanted by-products such as char/fuel-gas.

There are many types of gasifiers which differ in terms of solids-handling (e.g. fixed-bed, entrained bed, fluidised bed, multiple beds), air/oxygen injection, operating temperature and pressure, tar- and ash/slag management. Engineering issues such as inherent heat/mass-transfer limitations, solids handling, ancillary equipment (e.g. air-separation) influence the scale for individual gasifiers. (e.g. Figure B.3.1. 1).

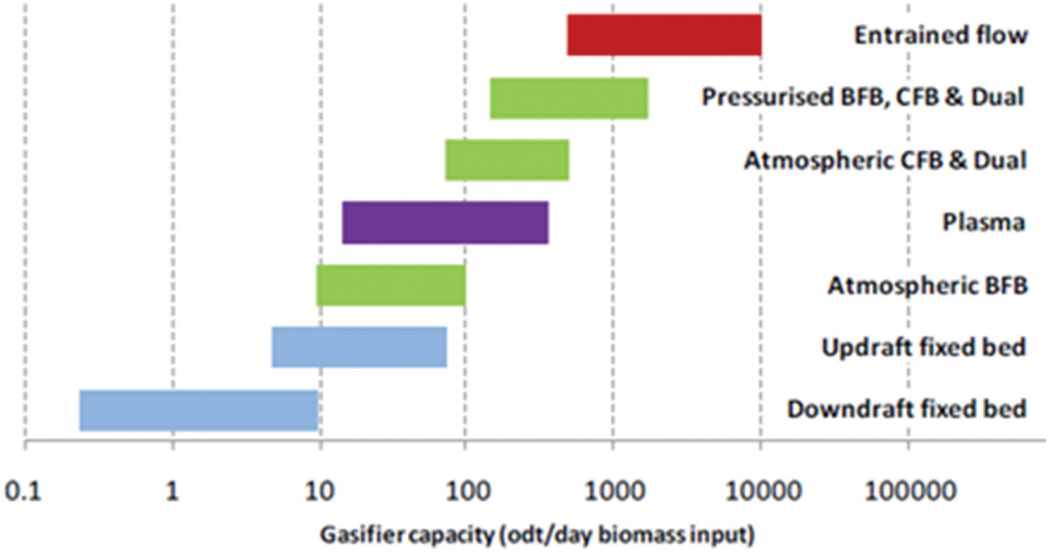


Figure B.3.1.1: Capacity range for different biomass gasifier technologies *(Review of technologies for gasification of biomass and wastes)*

The preferred designs for gasifying biomass include entrained flow, fluidised bed (FB) and plasma gasifiers. Entrained flow gasifiers require fairly uniform feedstock, so might not be suitable for waste-derived streams. Plasma gasifiers operate at very high temperatures which may help with inorganics in waste-derived feedstocks; on the other hand, they may be more costly to build and operate (*A review on the production of renewable aviation fuels from the gasification of biomass and residual wastes*). Plasmas are targeted largely towards very low calorific value that would normally go to landfill, where the additional energy costs are offset by the avoided negative value of disposal.

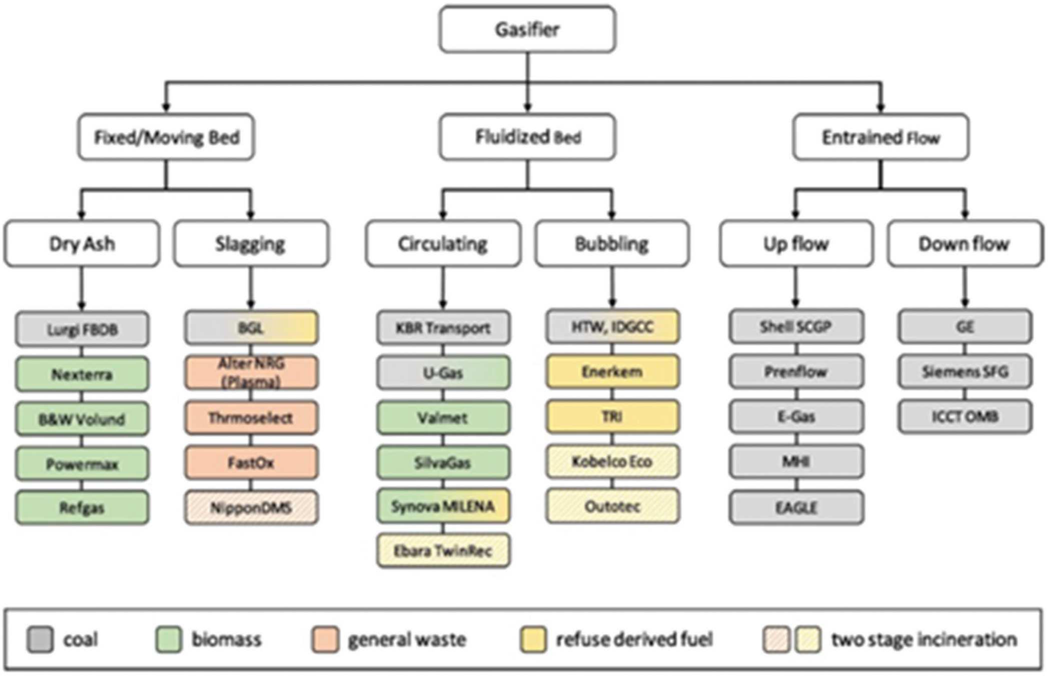


Figure B.3.1.2: Gasifier technologies and applicability to different feeds *(A review on the production of renewable aviation fuels from the gasification of biomass and residual wastes*, Figure 3)

Biomass gasification for power or CHP is fairly common, mainly as small/modular units fired with wood pellets; capacities are typically 0,5 to 5 MW-th (IEA, 2019). There are also some larger facilities (e.g. RWE, Geertruidenberg) which exceed 50 MW-th and approach the scale required for chemical synthesis (>200 to 250 ton/day of biomass.) A few commercial biomass/MSW gasifiers have been built to provide syngas for methanol, ethanol or FT-syncrude production, with liquid production typically in the range 50–150 ton/day; some larger ones are planned (*A review on the production of renewable aviation fuels from the gasification of biomass and residual wastes*, BioTFueL, Siemens Energy). Table B.3.1.1 shows a selection of waste-conversion facilities, both constructed (C) and planned (P).

Table B.3.1.1: MSW Conversion facilities, constructed and planned

Feedstock	Developer	Project name	Gasifier technology	Conversion technology	Status	TRL	Product, ton/day
MSW	Fulcrum	Sierra Biofuels	TRI	FT	C	8	85
MSW	Fulcrum	Centerpoint Biofuels	TRI	FT	P	9	300
MSW	Fulcrum	Essar Liverpool, UK	TRI	FT	P	9	250
MSW	Enerkem	Edmonton Alberta	Enerkem	EtOH	C	8	90
MSW	Enerkem	Vanerco Biofuels	Enerkem	EtOH	P	9	100
MSW	Enerkem	W2C Rotterdam	Enerkem	MeOH	P	9	650
MSW	Enerkem	Ecoplanta	Enerkem	MeOH	P	9	800
MSW	Enerkem	Invergrove Heights	Enerkem	EtOH	P	9	180
MSW	BioFuel	Haugesund, Norway	AlterNRG	FT	P	n/a	170
MSW	BioFuel	Fredrikstad, Norway	AlterNRG	FT	P	n/a	20
MSW/ Wood	Aemetis	Aemitis bioethanol	InEnTec	EtOH	P	8	110
MSW	Altalto	Immingham, UK	TRI	FT	P	n/a	n/a
MSW	Illinois Clean Fuels	n/a	n/a	FT	P	n/a	3 500

Synthesis gas cleaning and conditioning

This is key for successful integration of gasification and FT technology. Raw synthesis gas contains impurities such as particulates, metals, chlorine, and sulfur which must be removed for both power and synthesis applications; the latter are more stringent. Tars also may be an issue with solid and liquid gasifier feeds, so some systems include catalytic tar conversion. In some cases, the synthesis gas CO:H_2 ratio must be adjusted to better suit the FT conversion technology; this is commonly carried out using water-gas shift catalysis.

FT synthesis

FT synthesis is an established catalyst process to convert H_2-rich syngas into hydrocarbon liquids (*Analysis of natural gas-to liquid transportation fuels via Fischer-Tropsch*). It is conventionally operated at 20–40 bar and 200–250 °C (Cobalt-based catalyst) or 300–350 °C (Iron-based catalyst). The primary product is a wide boiling range 'syncrude' comprising mainly linear aliphatic hydrocarbons with carbon-numbers in the range 4 to >40 with a boiling range of 40 °C to >500 °C.

Operational world scale FT-plants include Shell's Pearl Gas-to-Liquids (GTL) plant in Qatar (*Advances in gas-to-liquids technology at Shell*) and Sasol's Secunda Coal-to-Liquids (CTL) plant in South Africa (*Upgrading of Fischer-Tropsch products to produce diesel*); both produce ca 140 kbbl/day (ca 15 kton/day) of liquids. The FT reaction is very exothermic, consequently the reactor must be able to handle large heat flux, which limits the capacity of individual FT reactors to roughly 500 to 2 000 ton/day depending on technology (*Conversion of syngas to diesel*); large facilities therefore may have several trains of FT reactors.

FT-wax hydrocracking

Typical FT-syncrude contains roughly equal parts of naphtha-range, diesel-range and high-boiling materials but – because they primarily comprise linear hydrocarbons – have high melting points and are generally unsuitable for fuels. FT-syncrude therefore is commonly hydrocracked to convert the high-boiling fraction into gasoline and diesel; this simultaneously isomerises the products to improve their low-temperature properties. HCK severity can be chosen to optimise the product distribution, particularly the balance between FT-jet, FT-diesel and higher boiling FT-products which are high-quality lubricant base stocks.

An important consideration is that HCK alone always gives a distribution of products from LPG to lubricants, although the 'shape' of the distribution can be adjusted. Production of LPG and naphtha is unavoidable; if it is uneconomic to collect them for sale, then they may have to be burned as fuel, e.g. to provide heat for the gasifier.

Wax HCK is established technology (*Fischer-Tropsch waxes upgrading via hydrocracking and selective hydroisomerization* and *Middle distillates from hydrocracking of FT waxes: Composition, characteristics and emission properties*). In principle, it resembles the HCK processes used in crude-oil refineries, but is optimised for cracking linear paraffins rather than the mixed paraffins and substituted aromatics found in refinery streams. FT-wax contains lower levels of contaminants (S, N, metals) than would be expected in refinery streams.

Mini- and micro-FT

A more recent trend involves downscaling the technology for use with (a) small-scale natural gas such as recovered flare-gas associated with crude oil production, and (b) syngas from biomass- and waste-gasifiers. The state of the small-scale FT market is reviewed annually by the World Bank's Global Gas Flaring Reduction Partnership (*Mini-GTL technology bulletin*); developments include 'micro- 'and 'mini-FT' systems with capacities from 5 to 500 ton/day. Nordic Energy has also recently reviewed this area on behalf of Danish Energy, SAS, and other Scandinavian partners. (Tables B.3.1. 2 and B.3.1. 3).

Table B.3.1.2: Scale of FT design, based on *Nordic GTL* (Table 3)

	Micro-GTL	**Mini-GTL**	**Small-scale**	**World-scale**
FT production, ton/day	1	10	100	>1 000
Type of operation	Unattended, modular	Moveable, modular	Stationary	Stationary

Three developers highlight some of the issues in downscaling:

- Velocys: small-scale FT reactor with advanced heat-transfer; it has a separate HCK reactor for product finishing. The FT technology has been tested at ca 25 ton/day ('Envia' project; (*Roll out of smaller scale GTL technology at ENVIA Energy's plant in Oklahoma City*) and is being commercialised as ca 135 ton/day (e.g. Redrock Biofuels, (*Velocys sells its second commercial license for FT renewable diesel and jet technology to Red Rock Biofuels* and *Fulcrum announces plans to develop SAF biorefinery in the UK*).
- Renovare fuels: modular GTL with production of up to 18 800 litres/day of FT-products (15 ton/day). This has a reduced FT-upgrading flow scheme where a specialised gas reformer eliminates the need for a separate shift-reactor and the FT technology is optimised to avoid the need for separate HCK.
- T2C (*Biogas to diesel*): skid-mounted modular GTL-plant making 111 gal/day (0,3 ton/day) of FT-diesel; this also has a reduced FT-upgrading flow scheme.

Table B.3.1.3: List of micro/mini-GTL developers *(Nordic GTL*, Table 4)

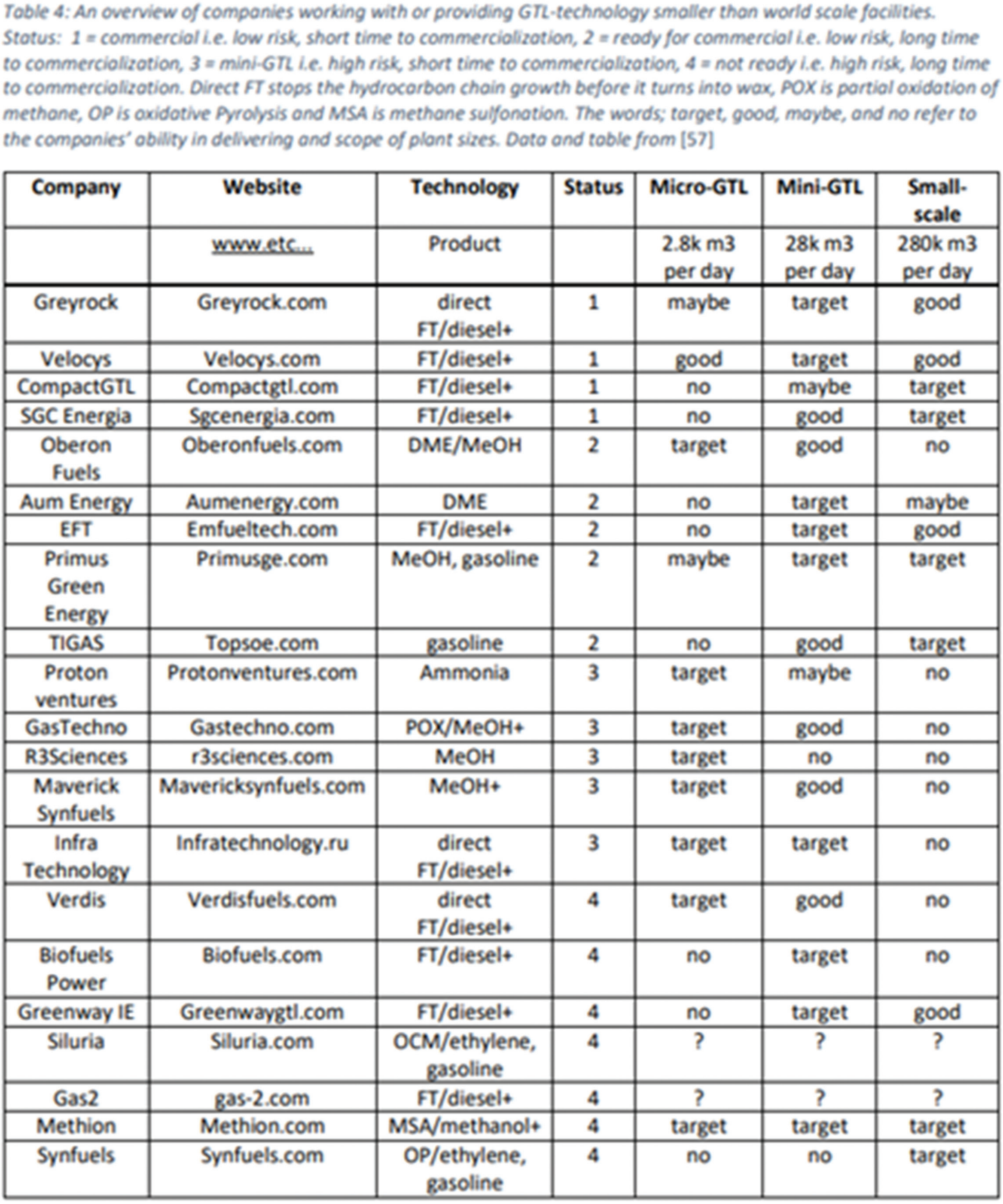


Table 4: An overview of companies working with or providing GTL-technology smaller than world scale facilities. Status: 1 = commercial i.e. low risk, short time to commercialization, 2 = ready for commercial i.e. low risk, long time to commercialization, 3 = mini-GTL i.e. high risk, short time to commercialization, 4 = not ready i.e. high risk, long time to commercialization. Direct FT stops the hydrocarbon chain growth before it turns into wax, POX is partial oxidation of methane, OP is oxidative Pyrolysis and MSA is methane sulfonation. The words; target, good, maybe, and no refer to the companies' ability in delivering and scope of plant sizes. Data and table from [57]

Company	Website	Technology	Status	Micro-GTL	Mini-GTL	Small-scale
	www.etc...	Product		2.8k m3 per day	28k m3 per day	280k m3 per day
Greyrock	Greyrock.com	direct FT/diesel+	1	maybe	target	good
Velocys	Velocys.com	FT/diesel+	1	good	target	good
CompactGTL	Compactgtl.com	FT/diesel+	1	no	maybe	target
SGC Energia	Sgcenergia.com	FT/diesel+	1	no	good	target
Oberon Fuels	Oberonfuels.com	DME/MeOH	2	target	good	no
Aum Energy	Aumenergy.com	DME	2	no	target	maybe
EFT	Emfueltech.com	FT/diesel+	2	no	target	good
Primus Green Energy	Primusge.com	MeOH, gasoline	2	maybe	target	target
TIGAS	Topsoe.com	gasoline	2	no	good	target
Proton ventures	Protonventures.com	Ammonia	3	target	maybe	no
GasTechno	Gastechno.com	POX/MeOH+	3	target	good	no
R3Sciences	r3sciences.com	MeOH	3	target	no	no
Maverick Synfuels	Mavericksynfuels.com	MeOH+	3	target	good	no
Infra Technology	Infratechnology.ru	direct FT/diesel+	3	target	target	no
Verdis	Verdisfuels.com	direct FT/diesel+	4	target	good	no
Biofuels Power	Biofuels.com	FT/diesel+	4	no	target	no
Greenway IE	Greenwaygtl.com	FT/diesel+	4	no	target	good
Siluria	Siluria.com	OCM/ethylene, gasoline	4	?	?	?
Gas2	gas-2.com	FT/diesel+	4	?	?	?
Methion	Methion.com	MSA/methanol+	4	target	target	target
Synfuels	Synfuels.com	OP/ethylene, gasoline	4	no	no	target

Summary

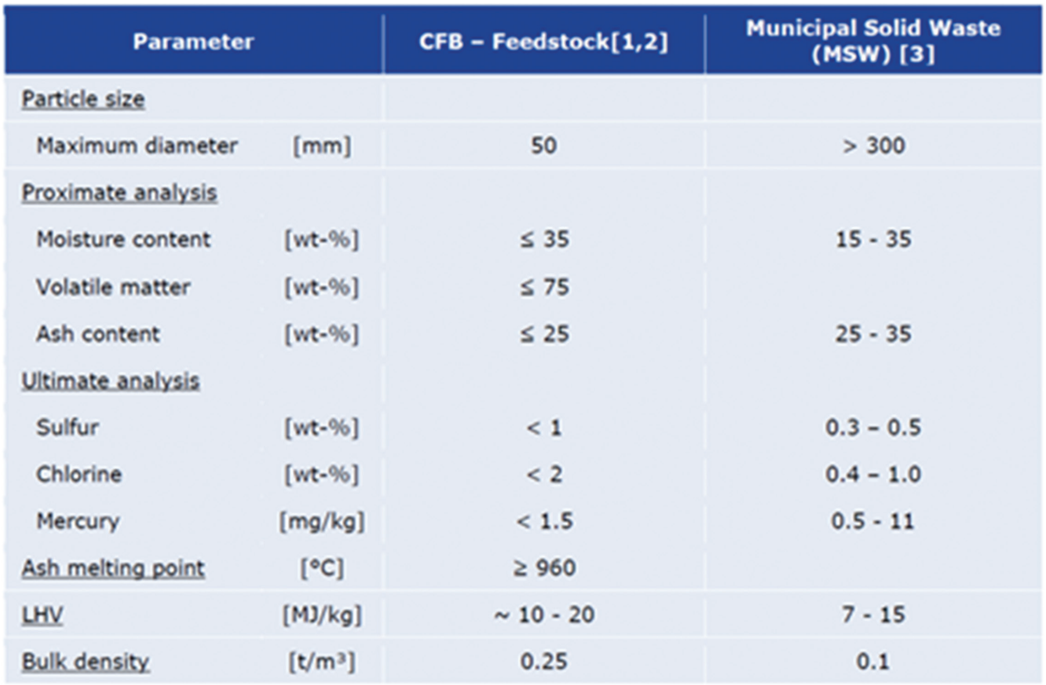
The FT technology landscape is complex, with a range of catalyst technologies (e.g. Fe-based, Co-based), process technologies (e.g. multi-tube, fluid-bed, modular) and a corresponding range of technology developers/providers/owners in a variety of different partnerships (e.g. Shell, Sasol, BP, Exxon, Johnson Matthey, Velocys, Axens.) There is a wide variety of technology available for 'primary conversion', i.e. gasification, syngas cleaning/conditioning, FT-synthesis, wax-HCK.

The main challenges are (a) effective downscaling to suit WTFs feed availability; (b) integrating the various technologies at a common scale, and (c) re-optimising technologies to allow simpler flow schemes or better integration with feedstock, especially if it has variable quality. The use of waste as gasifier feed presents additional challenges such as feedstock variability, tar-handling, particulates, and syngas purity. Water supply may also be a challenge, e.g. provision of a new water supply is cited as key to Enerkem's MSW-to-Ethanol plant at Invergrove Heights (*Enerkem's proposed $200 million Twin Cities facility depends on new wastewater treatment plant*).

B.3.2 Feedstock

As discussed, the heterogeneity and variability of mixed waste has a big impact on gasifier design and operation. For waste streams, pre-treatment generally involves removal of inorganics (e.g. metals, concrete, glass); drying to reduce the moisture content, homogenisation/size-reduction to facilitate solids handling and gasifier operation (*Status report on thermal gasification of biomass and waste 2019*). An indicative list of requirements is shown in Table B.3.2.1; exact limits are unit-dependent, with entrained bed gasifiers likely to be the most stringent, then fluidised-bed gasifiers, and finally plasma gasifiers likely the least stringent (*Review of technologies for gasification of biomass and wastes*). There may also be limits on potentially hazardous materials, e.g. As, Cd, Hg, F and Br.

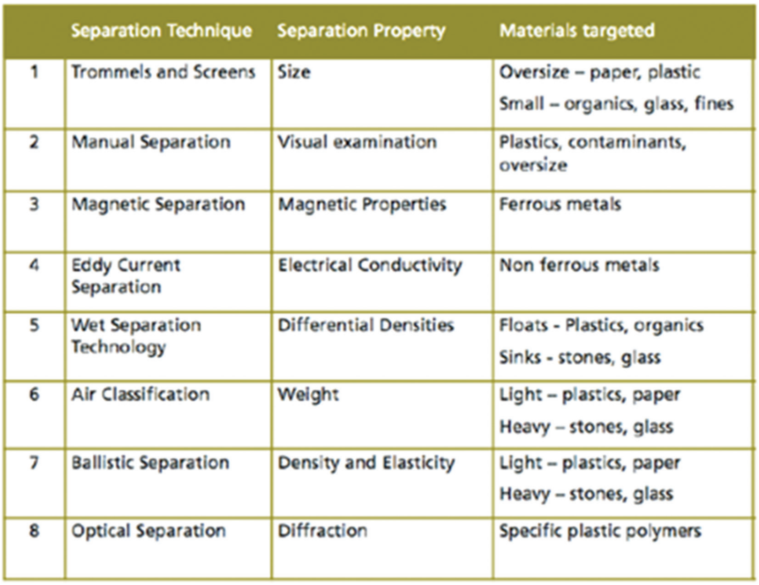
Table B.3.2.1: Feed requirements for CFB gasifier *(Status report on thermal gasification of biomass and waste 2019,* Table 1)



Parameter		CFB – Feedstock[1,2]	Municipal Solid Waste (MSW) [3]
Particle size			
Maximum diameter	[mm]	50	> 300
Proximate analysis			
Moisture content	[wt-%]	≤ 35	15 - 35
Volatile matter	[wt-%]	≤ 75	
Ash content	[wt-%]	≤ 25	25 - 35
Ultimate analysis			
Sulfur	[wt-%]	< 1	0.3 – 0.5
Chlorine	[wt-%]	< 2	0.4 – 1.0
Mercury	[mg/kg]	< 1.5	0.5 - 11
Ash melting point	[°C]	≥ 960	
LHV	[MJ/kg]	~ 10 - 20	7 - 15
Bulk density	[t/m³]	0.25	0.1

Pre-treatment normally involves a series of steps involving different separation technologies targeting different materials, e.g. Table B.3.2. 2. There may also be biological treatments such as partial composting or AD to remove active organic materials.

Table B.3.2.2: MSW Pre-treatment techniques *(Status report on thermal gasification of biomass and waste 2019)*



	Separation Technique	Separation Property	Materials targeted
1	Trommels and Screens	Size	Oversize – paper, plastic Small – organics, glass, fines
2	Manual Separation	Visual examination	Plastics, contaminants, oversize
3	Magnetic Separation	Magnetic Properties	Ferrous metals
4	Eddy Current Separation	Electrical Conductivity	Non ferrous metals
5	Wet Separation Technology	Differential Densities	Floats - Plastics, organics Sinks - stones, glass
6	Air Classification	Weight	Light – plastics, paper Heavy – stones, glass
7	Ballistic Separation	Density and Elasticity	Light – plastics, paper Heavy – stones, glass
8	Optical Separation	Diffraction	Specific plastic polymers

B.3.3 Primary conversion product

As described earlier, the FT-products may come in two forms, depending on the design of the FT process in the primary conversion plant: (a) 'FT without HCK' makes a wide-boiling syncrude, and (b) 'FT with HCK' makes finished FT-naphtha and FT-diesel. FT technologies used at small scale are unlikely to give finished FT-products (i.e. naphtha, jet, or diesel), whose properties differ from equivalent products made in large-scale GTL and CTL-plants. At present, FT-diesel and FT-naphtha already enter the refined product supply chain, but FT-syncrude generally does not.

The exact properties of FT-products are unit-specific, but in general:

- FT syncrude (*Status and future opportunities for conversion of synthesis gas to liquid energy fuels: Final report*, Fig 29) is typically a wide-boiling hydrocarbon wax typically comprising linear-paraffins (Co-based catalysis) or substantially linear paraffins and olefins (Fe-based catalysis.) The carbon-number range depends on the technology, but 'raw' syncrude might contain C5 to >C40, hence a boiling range of 40 °C to >500 °C and roughly equal parts of naphtha-range, diesel-range and high-boiling materials. It might be optimised for ease of transport, e.g. liquid like C5-C20 vs solid >C20 either by optimisation of the FT-process or by product fractionation.
- FT-diesel (*Properties and performance of gas-to-liquids Fischer-Tropsch diesel fuels* and *GTL knowledge guide V2*) resembles finished EN590 diesel, but is very low in aromatics and has a significantly lower density and higher cetane rating. Low density may limit blends to perhaps 10–20 % if no changes are made to refinery operation; on the other hand, it might allow refinery reoptimisation to use higher density crude-derived blend stocks.

FT-naphtha (patent no. WO 2017/093203, 2017) is very low in aromatics and olefins compared with EN228 gasoline which leads to a poor octane rating which may limit its use in EN228 finished fuel. It might be better used as steam-cracker feedstock for petrochemical production of C2/C3 olefins.

B.3.4 Integration with refined product supply chain

WTF production at say 100–500 ton/day is relatively small compared with the 'notional' EU refinery, i.e. 20 kton/day of crude producing 4 and 10 kton/day of gasoline and diesel. 500 ton/day would represent only a few% of crude throughput, 10–15 % of FCC throughput and 20 % of HCK throughput.

Fulcrum's 'Sierra' WTP plant is under construction (*Clean, low-cost, sustainable*). Once it is completed, it is expected to provide ~85 ton/day of FT-syncrude to Marathon's Martinez refinery (161 kbbl/day, ~20 kton/day of crude). There is no information about how it is being processed.

Waste-to-fuels plant design

Integration options depend on the sophistication of the WTF plant, primarily whether (a) it has wax HCK and makes 'finished' FT-naphtha, FT-diesel etc., or (b) it has no wax hydrocracking and makes just a 'raw' FT syncrude.

1. **Primary products are finished FT-products**
   Finished FT-products such as gasoline, jet or diesel would likely be used as 'drop-in' fuels and blended directly to make finished transport fuels. This would operate in the same way as GTL-derived FT-diesel is used in EU refineries today.

2. **Primary product is FT-syncrude**

   In principle, FT-syncrude could be used as co-feed to the refinery CDU, i.e. it would be treated as a low-sulfur paraffinic crude. Studies (e.g. *Fischer–Tropsch fuels refinery design*) show the parallels between 'crude-oil' and 'Fischer-Tropsch' refinery design. The lighter FT-fractions would go with the straight-run naphtha, kerosene, and diesel as they made their way through the refinery; being mainly linear paraffins, they would not react, so they might unnecessarily take up hydro-desulfurisation capacity.

   The blend limit for FT-syncrude in the CDU would depend on the other crudes being run. Being very paraffinic, the syncrude might interact with fossil crudes causing precipitation. In addition, the relative ratio of FT:crude in each fraction could also affect its properties, e.g. freeze point, cloud-point.

   Heavier FT-fractions would go with VGO as fuel-oil or for co-processing in FCC/HCK units. There is limited public information about co-processing FT wax with VGO:

   - HCK (*Hydrocracking vacuum gas oil with wax* and *Hydrocracking of a heavy vacuum gas oil with Fischer–Tropsch wax*) – under conditions suitable for processing refinery VGO, FT syncrude or FT-heavy wax appears to convert relatively easily to light products but may have an inhibiting effect on the conversion of the VGO.
   - FCC (*Production of clean transportation fuels and lower olefins from Fischer-Tropsch Synthesis waxes under fluid catalytic cracking conditions – The potential of highly paraffinic feedstocks for FCC*) – under conditions suitable for processing refinery VGO, FT-syncrude is almost completely converted; the main liquid product is gasoline.

Running FT-syncrude to the CDU might be considered as high-risk – any disruption to the CDU affects the whole operation of the refinery. There might be other 'entry points' for syncrude, e.g. direct to conversion units such as FCC and HCK. FCC is generally considered the more 'robust' unit, but its yields and product qualities are poorer.

Location of waste-to-fuels plant

Finished FT-naphtha and FT-diesel in principle could make use of existing logistics infrastructure. FT-syncrude might require dedicated logistics depending on its carbon-number range and hence its melting point. For example, C5-C20 might be sufficiently fluid but higher melting material might need heated storage.

A WTF facility could be co-located at a refinery with direct integration with refinery conversion processes and utilities. This would allow use of all FT products from LPG to heavy wax, and integration regarding utilities, hydrogen, etc. It might also allow waste aggregation if existing transport links might be used, e.g. barge, rail.

B.4 MUNICIPAL BIOWASTE (INCL. FOOD AND GARDEN WASTE)

B.4.1 Process

Anaerobic digestion

AD is a biological process where micro-organisms convert bio-degradable organic material into biogas in the absence of oxygen; it is an established technology for the production of renewable energy (*Biogas from crop digestion*). Commercial AD plants treat a wide variety of raw feeds (*Feedstocks*), including post-consumer and production food waste, manure, sewage sludge and purpose grown crops. Raw biogas contains 40–70 % CH_4, balance CO_2 + residual moisture and contaminants such as ammonia, hydrogen sulfide and siloxanes; the exact composition depends on the type of feedstock. It is produced at slightly above ambient temperature and pressure, so is either combusted to provide electricity (often combined heat and power, CHP) or purified to produce pipeline-quality bio-methane.

Different AD technologies operate at different temperatures, different residence times allowing optimisation to specific feedstocks, solids-content, and economics scales. Different stages/types of digestion require different microorganisms. For this study, an important distinction may be 'wet-' vs 'dry-AD' (*State-of-the-art dry and wet anaerobic digestion systems for solid waste* and *Wet and dry anaerobic digestion processes*):

- In wet-AD, the feedstock is slurried (5–15 % dry matter) and processed in large, stirred tanks; continuous processing may be possible. This type of technology is relatively common.
- In dry-AD, the feedstock may contain >30 % dry matter and may have to be stacked as a solid, with the process liquid being recirculated to percolate through the beds. It is generally a batch process. This is a less common technology, but is commercially available (e.g. *Wet and dry anaerobic digestion processes* and *Innovative biogas technology*).

Biogas requires little pre-treatment before being used for heat/power, but needs upgrading and compressing before injection into the natural gas grid or use as compressed natural gas (CNG) road fuel. Upgrading technologies (e.g. *Biogas upgrading to Vehicle Fuel Standards and grid injection*) include absorption; adsorption (e.g. pressure swing adsorption (PSA)); membrane separation and cryogenic distillation, and sorbents/scrubbers for NH_3 and H_2S.

AD capacities in the UK (*State-of-the-art dry and wet anaerobic digestion systems for solid waste*) are typically 500 to 1 500 kW-e, so a large AD plant might produce ca 7 000 Nm3/day or 5 ton/day of bio-methane. Yields are typically 100–500 Nm3-methane per ton of dry crops or 15–30 Nm3-methane per ton of manure or other wet feeds. (*State-of-the-art dry and wet anaerobic digestion systems for solid waste* and *Biogas upgrading to Vehicle Fuel Standards and grid injection*). It is an established commercial technology (e.g. Figure B.4.1.1, *State-of-the-art dry and wet anaerobic digestion systems for solid waste*).

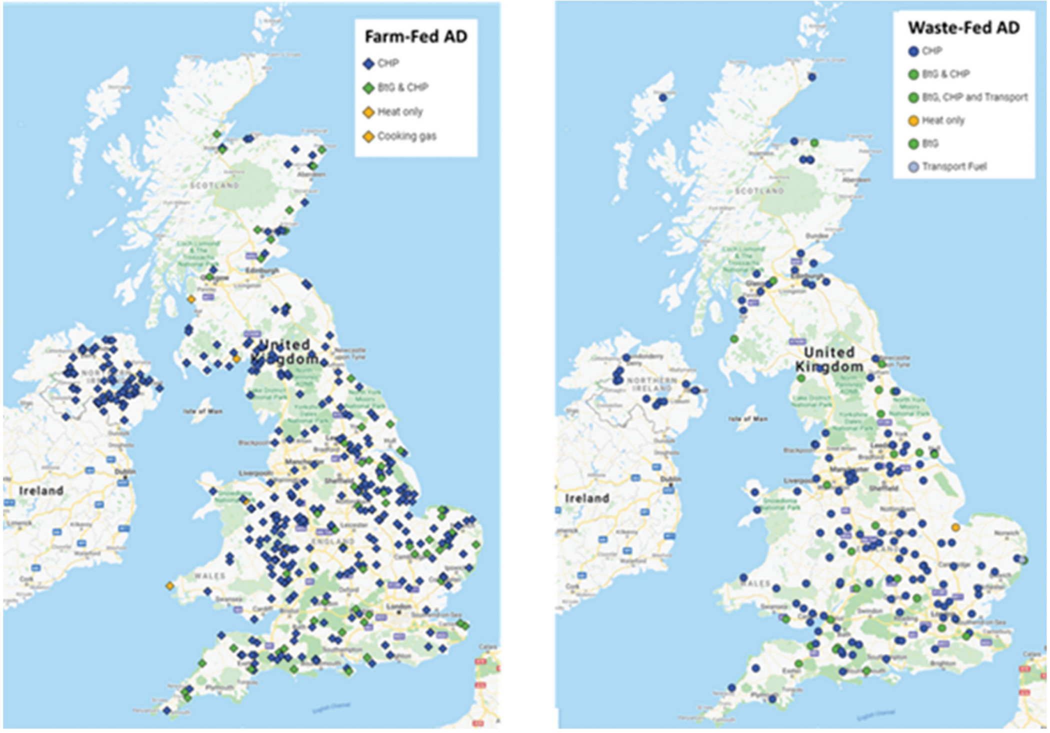


Figure B.4.1.1: AD plants in UK – farm-fed and waste-fed *(State-of-the-art dry and wet anaerobic digestion systems for solid waste)*

FT-synthesis to fuels

Conversion of biogas to FT-products could proceed either by:

1. **Methane-only** – biogas is treated to remove impurities and separate the methane component; the CO_2 is vented (possibly with carbon capture, utilisation and storage (CCSU)). FT synthesis can either be handled locally using micro/mini-FT technologies described in B.3.1, or centrally using biomethane aggregated via the natural gas grid.
2. **Methane+CO_2** – biogas is treated only to remove impurities then fed with steam and air to a 'tri-reformer' (*Biogas reforming to syngas: A review*). This provides a combination of 'steam reforming' (CH_4 + H_2O to syngas) and 'dry-reforming' (CH_4 + CO_2 to syngas) with some methane combustion to provide the heat of reaction. Additional heat may be provided by combusting light by-products from the FT-synthesis. This approach is still under development, e.g. Renovare and T2C mini/micro-GTL discussed in B.3.1.

B.4.2 Feedstock

AD plants are already widely used for conversion of food waste, plant material such as: silage (i.e. grass); straw; leaves; nettles, and energy crops such as beet, alfalfa, and miscanthus. These are usually segregated so the AD feed is fairly homogeneous. AD does not break down lignin and is not always suitable for 'woody' garden waste; composting is often considered the better option for mixed feeds (note that composting is an aerobic process which does not produce methane). Key questions for mixed food/garden waste concern (a) feedstock variability from day-to-day, and (b) the range of digestibility of the plant matter within each batch, e.g. 'leafy' vs 'woody' and whether it is best handled by 'wet' or 'dry' AD or composting. Surveys of 'biowaste' treatment in Europe (*Compost production in Europe* and *Bio-waste in Europe – Turning challenges into opportunities*) show that composting is more common than AD, but that the balance between the two technologies differs considerably between countries, as does the balance between mixed and segregated feeds. Some technology providers already offer integrated AD and composting plants, with some operational in North America and Europe (*Integrating anaerobic digestion with composting* and *Producing biogas and compost from waste*). These facilities appear to use segregated food and plant waste, so that AD handles materials which might be reactive and methane-forming, with the aerobic composter taking the AD residues and 'indigestible' material. The plant products are biogas and organic-rich compost, thus minimising GHG emissions which might result if the mixed waste was simply landfilled or composted. The Biogas website suggests that composting will remain the best option for co-collected food/garden waste, or for woody garden waste that is collected on its own.

B.4.3 Primary conversion product

The primary products are either FT wax or fractionated FT fuels as discussed in B.3.1. The main difference is likely to be smaller scale from AD-based operations; there may be minor differences in FT-product distribution and properties.

B.4.4 Integration with refined product supply chain

This has the same opportunities and limitations as waste-gasification (B.3.1), except that the individual plants are likely to be smaller.

ANNEX C
COST DRIVERS

This annex provides details of the cost drivers for each pathway. These are summarised in the cost drivers and investment costs (3.2.1).

Table C.1: Cost drivers for mixed plastic waste pyrolysis refining

Cost driver	Factors that impact the cost driver
CAPEX	**Pyrolysis** Pyrolysis plants tend to be scaled to fit the local availability of feedstock. However, scale, and therefore total project investment, could be limited by reactor size Heat is supplied to the pyrolysis reactor indirectly, in many cases by combusting light gases produced from the pyrolysis reaction itself in a chamber external to the pyrolysis reactor. This means that the amount of heat that can be transferred is proportional to the surface area of the pyrolysis reactor. To achieve higher throughputs, the pyrolysis reactor volume must increase, but since the surface area to volume ratio decreases with increasing volume, this means that in order to supply sufficient heat for the pyrolysis reaction, there is a maximum volume of any given pyrolysis reactor. This issue can be overcome by building multiple parallel reactors; however, this would mean that economies of scale are diminished (*Plastics to oil products*) **Refining** Some pyrolysis oil fractions may be able to be blended directly with fuel products or could be hydrotreated. It is expected that in this pathway the pyrolysis oil would be provided without fractionation to the refinery for further processing using existing process units, rather than new small scale fractionation units being constructed, and integrated with the pyrolysis units Pyrolysis oil that has not been fractionated could be fed in to refinery CDU, FCC or HCK. These units are already widely installed as part of EU refineries so no significant CAPEX to build these would be required. However, there is a knowledge gap around the extent to which these oils can be co-processed in existing refinery units. The technical factors (e.g. reactive olefin content of the pyrolysis oil, impurities) impacting the potential for pyrolysis oils from plastic to be co-processed are covered in more detail in Annexes A and B. If these technical factors mean that the pyrolysis oil cannot be co-processed at the desired volumes in existing equipment, additional CAPEX may be required in terms of either low-cost modifications (e.g. higher pressure, modifications to the catalyst bed) or a new ('non-refinery') unit (e.g. to process highly reactive feeds with high olefins content)

Table C.1: Cost drivers for mixed plastic waste pyrolysis refining (continued)

Cost driver	Factors that impact the cost driver
OPEX	**Pyrolysis** Most (often all) energy needed for the pyrolysis is contained within the plastic, and a significant proportion is used for this energy. Although this means that limited net energy input is required, it results in yield losses in the process. It also means that the feedstock cost is very sensitive to the plastic waste price **Refining** Hydrogen consumption in the refinery hydrotreater and HCK is expected to be higher when co-processing higher percentages of pyrolysis oil than when processing virgin fossil hydrocarbons only, due to the higher levels of impurities. The extent of this when processing the pyrolysis oil in an existing unit will be influenced by the pyrolysis oil composition. The cost of the hydrogen will of course be dependent on the source Related to the discussion on a requirement for CAPEX, there may be some OPEX impact when co-processing pyrolysis oil (e.g. higher pressure) but there are significant knowledge gaps surrounding these possible cost drivers
Feedstock	**Mixed plastic waste** Post-consumer mixed plastic waste (largely packaging) is the current focus for pyrolysis project developers, and this is a major driver of economics as the plastic waste is used in the process and to provide the majority/all of the process energy. In European countries, many local authorities are charged gate fees (per tonne) by recyclers, so where pyrolysis plants are classed as recycling, this can currently contribute a significant proportion of a producer's revenue

Table C.2: Cost drivers for sewage sludge HTL to HTL oil refining

Cost driver	Factors that impact the cost driver
CAPEX	**HTL to HTL oil** The HTL reactor is expected to account for the highest share of the HTL-to-HTL oil step (*Conceptual biorefinery design and research targeted for 2022: Hydrothermal liquefaction processing of wet waste to fuels*). The severe operating conditions (high temperature and pressure – more details in the OPEX section and Annex B.2), result in high cost for the reactor compared to some other less severe processes HTL plants using sewage sludge will tend to be scaled to fit the local availability of feedstock. Although currently at an earlier stage than fast pyrolysis, HTL plants have the potential to be more scalable than pyrolysis plants, and therefore could potentially see more economies of scale savings in the future. By providing the heat directly (via contact of the sewage sludge with supercritical water), HTL overcomes the heat transfer limitations of pyrolysis (surface area to volume ratio) and therefore can be built at larger scale **Refining** HTL with upgrading to fractionated products could be directly blended with fuels; however, it is expected that in this pathway the HTL oil would be provided without upgrading to the refinery for further processing, using existing process units rather than new small scale upgrading units being constructed and integrated with the HTL units The HTL oil could be processed in refinery hydrotreaters, FCCs and HCK. These are already widely installed as part of EU refineries, so no significant CAPEX is expected to be required to build these units. However, there is a knowledge gap around the extent to which these oils can be co-processed in existing refinery units. The technical factors (e.g. oxygenate levels, impurities) impacting the potential for HTL oils from sewage sludge to be co-processed are covered in more detail in Annexes A and B. HTL oils benefit from a much lower oxygen 5–10 wt % O content than fast pyrolysis oil from biomass, but they can still be very acidic so still might need specialised metallurgy. The acidity may need to be pre-treated in a specialised new unit, possibly a stabilisation hydrotreatment unit; however, there is a knowledge gap around what would be required and the CAPEX impact

Table C.2: Cost drivers for sewage sludge HTL to HTL oil refining (continued)

Cost driver	Factors that impact the cost driver
OPEX	**HTL To HTL oil** HTL requires significant quantities of heated (~ 350–450 °C) and pressurised water ~3 000 psia (200 Bara) and therefore this may represent a major cost driver depending on the local energy costs and also the feedstock used (*Conceptual biorefinery design and research targeted for 2022: Hydrothermal liquefaction processing of wet waste to fuels*). Some of the released gases are expected to be recovered from the reactor (accounting for ~20 % of the heat) and could in part be used to provide process energy, but unlike plastic waste pyrolysis, purchased fuel (e.g. natural gas) is expected to be required **Refining** In the refinery, the hydrogen cost for the HDT and HCK is expected to be a large cost driver for these process steps. Hydrogen consumption in the refinery hydrotreater and HCK is expected to be higher when co-processing higher percentages of HTL oils than when processing fossil hydrocarbons only, due to the higher levels of impurities. The extent of this when processing the HTL oil in an existing unit will be influenced by the HTL oil composition. The cost of the hydrogen will of course be dependent on the source (e.g. grey, blue, green)
Feedstock	**Sewage sludge** The cost of sewage sludge could be a major determinant of the process economics; however, it can be sourced at zero (*Conceptual biorefinery design and research targeted for 2022: Hydrothermal liquefaction processing of wet waste to fuels*), low cost or sometimes a gate fee can be charged. Studies (*Conceptual biorefinery design and research targeted for 2022: Hydrothermal liquefaction processing of wet waste to fuels*) assume that sludge processing would be co-located with the water-treatment plant in order to avoid transport of wet sludge. Some sewage sludge does have some potential value when used as fertiliser. This differentiates it from other wastes considered in this study that do not have direct uses without further processing

Table C.3: Cost drivers for mixed residual waste gasification to FT-wax refining

<table>
<tr><th>Cost driver</th><th>Factors that impact the cost driver</th></tr>
<tr><td>CAPEX</td><td>
Gasification

There are several different types of gasifiers (major categories include: fixed bed; entrained flow; fluidised bed and plasma) and these vary in complexity, and therefore CAPEX. These are summarised in Figure C. 1

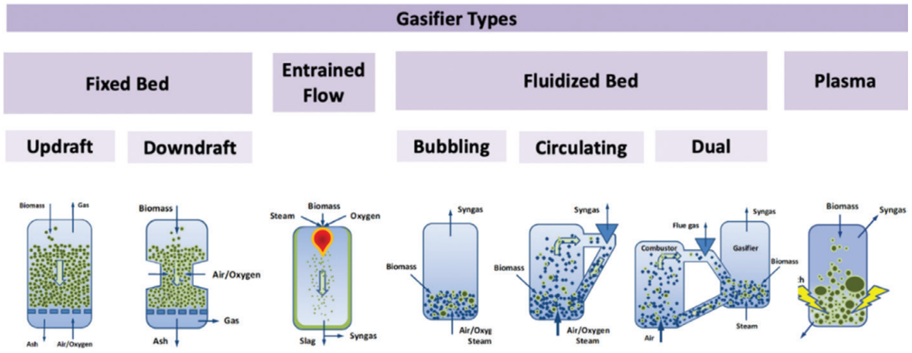


Figure C.1: Gasifier types *(Review of technologies for gasification)*

As well as the gasifier type employed, the scale will influence the CAPEX significantly. The scale is dependent on the feedstock volumes available to be processed, and also the gasifier types used (Figure C. 2). Current commercial gasifiers consuming fossil feedstocks such as coal or heavy fuel oil are significantly larger than those based on waste feedstocks or biomass

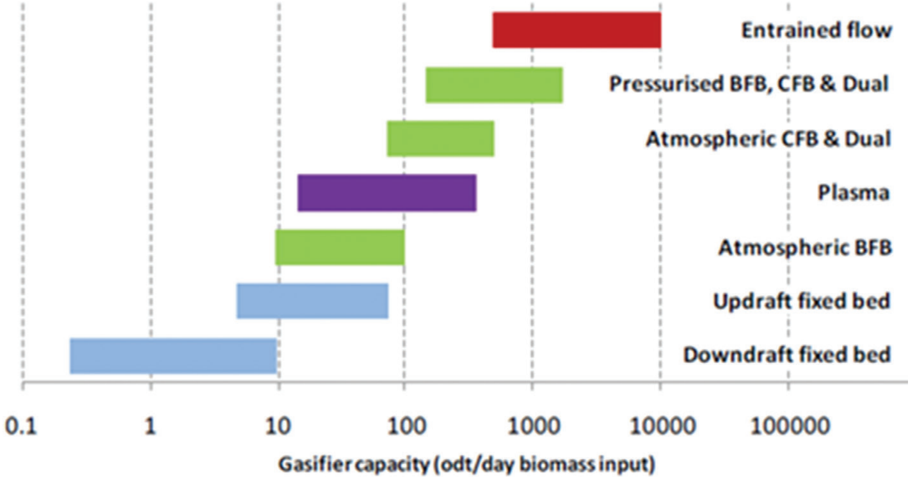


Figure C.2: Capacity range for different biomass gasifier technologies *(Review of technologies for gasification)*
</td></tr>
</table>

Table C.3: Cost drivers for mixed residual waste gasification to FT-wax refining (continued)

Cost driver	Factors that impact the cost driver
	FT The syngas from waste gasification is likely to need significant cleaning, and waste feedstocks tend to result in a syngas that needs more cleaning for FT than some fossil feedstocks. Synthesis reactions usually require syngas which is richer in hydrogen, so plants include syngas cleaning and also a 'shift-reactor' to adjust the CO/H_2 ratio or are supplemented with additional hydrogen. CAPEX required for these steps may be significant; however, it is expected to depend on the gasifier type employed, feedstock composition and requirements for downstream processing The FT reaction is very exothermic; consequently the reactor design needs to account for this, and the scale of the reactors is limited, and several trains are required to reach larger scales. These factors add to the CAPEX of the FT-reactor process step **Refining** If the WTF plant makes (a) 'finished' FT-naphtha, FT-diesel etc., or (b) it has no wax HCK and makes just a 'raw' FT syncrude, finished FT-products such gasoline, jet or diesel would likely be used as 'drop-in' fuels and blended directly to make finished transport fuels. This would operate in the same way as GTL-derived FT-diesel is used in EU refineries today and therefore would not require additional CAPEX in refineries FT syncrude could be processed in HCK, FCCs or CDUs which are all already widely installed as part of EU refineries, so no significant CAPEX is expected to be required to build these. However, there are knowledge gaps surrounding the processing of FT syncrude and there may be limits to how few it can be co-processed in existing assets. In addition, these limits for co-feeding FT syncrude to HCK or FCC are likely to be unit-specific subject to both process operation and final product properties
OPEX	**Gasification** The heat needed for the gasification reactions is usually provided by the partial combustion of a portion of the feedstock in the reactor with a controlled amount of air, oxygen, or oxygen-enriched air. Therefore, the economics of the feedstock are an important determinate of the energy costs for the processes. Heat can also be provided from external sources (e.g. superheated steam) or incorporate a high temperature combustor and heat transfer to the gasification vessel but the requirement for this depends on the gasifier technology The costs related to the oxidant are also important drivers. These depend on whether oxygen, air or steam is used. For gasifiers where FT is the downstream process, oxygen is expected to be used. Using oxygen is often expensive and intrinsically risky which can add cost

Table C.3: Cost drivers for mixed residual waste gasification to FT-wax refining (continued)

Cost driver	Factors that impact the cost driver
	FT FT synthesis is conventionally operated at 20–40 bar and 200–250 °C (cobalt-based catalyst) or 300–350 °C (iron-based catalyst) and is very exothermic, hence the energy costs for this step of the process are not a key consideration The FT catalysts are deactivated by sulfur poisoning, and this adds costs either in sulfur removal or, if it is not removed sufficiently, loss of catalyst activity and lifetime **Refining** Hydrogen consumption in the refinery hydrotreater and HCK is expected to be higher when co-processing higher percentages of FT syncrude than when processing only fossil hydrocarbons, due to the higher levels of impurities. The extent of this when processing the FT syncrude in an existing unit will be influenced by the FT syncrude composition. The cost of the hydrogen will be dependent on the source (e.g. grey, blue, green)
Feedstock	**Mixed residual waste** Plants are typically sited close to areas with sufficient volumes of waste generation, taking into account the local waste composition, and current alternative waste fates (landfilling, incineration, recycling, etc.) which may have long-term contracts for waste treatment. Importantly, the economics of plants using MRW depends on receiving gate fees for waste treatment, which vary considerably between jurisdictions MRW can also be processed to form RDF, by removing recyclable or non-combustible materials, shredding, and baling. Both Enerkem (gasification to methanol) and Fulcrum (gasification + FT) use RDF as the primary feedstock for their processes

Table C.4: Cost drivers for municipal biowaste (incl. food and garden waste) AD to biogas, to bioCH_4, to FT-wax refining

Cost driver	Factors that impact the cost driver
CAPEX	**AD to biogas and upgrading to bioCH_4** Capital costs for AD often account for over 50 % of overall AD costs (assuming a zero cost for feedstock), with the remainder operational and maintenance (O&M) costs (International Energy Agency (IEA), 2020)[4] Biomethane is produced from biogas by removing the CO_2 and other contaminants ('upgrading') via scrubbing, membrane, or cryogenic separation (*Technologies for biogas upgrading to biomethane: A review*). The overall cost for this step is lower than the biogas production step, but the CAPEX of the upgrading step is still important. The CAPEX varies depending on separation technology used. Today, most use physical scrubbing using water (*Outlook for biogas and biomethane: Prospects for organic growth*) **FT** See C.3. The main difference is likely to be smaller scale from AD-based operations **Refining** See C.3
OPEX	**AD to biogas and upgrading to bioCH_4** For AD, O&M includes ordinary and extraordinary maintenance, labour costs, and energy required to operate the system. These are relatively low for AD generally For the upgrading step, energy and water can be significant cost drivers, depending on regional utility costs (*Technologies for biogas upgrading to biomethane: A review*) **FT** See C.3 **Refining** See C.3
Feedstock	**Municipal biowaste (incl. food and garden waste)** AD plants are already widely used for conversion of food and garden waste. In some countries, food and garden waste is separated out into separate bins by the consumer (i.e. source separated) and this is collected as part of local authority collections and taken to AD or industrial composting facilities. The AD producer receives a gate fee. This can become an important influence on the AD producer's economics

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[4] Capital costs have been levelled for the production lifetime of each technology.

ANNEX D
POLICY AND REGULATION

Further detail has been provided for specific policies listed in Table 14 to explain how waste feedstocks are affected differently, the uncertainties that exist and the knowledge gaps that have been identified. Examples of targets and measures relating to these policies have also been included.

RED II

The Recast of the Renewable Energy Directive (RED II) sets a target of 14 % renewable energy in the transport sector by 2030. Within this, EU MSs are required to oblige fuel suppliers to supply 1,75 % of their fuel from advanced biofuels. This is then double counted to make up a minimum share of 3,5 % of the 14 % renewables target. Advanced biofuels are defined under Annex IX Part A based on a list of feedstocks that are mostly produced from wastes and residues associated with lower risks of indirect environmental and socio-economic impacts compared to conventional feedstocks.

Additional feedstocks can be added to these lists in Annex IX, but not removed, through the adoption of delegated acts by the European Commission, by considering sustainability criteria; GHG savings; risks of market distortion; environmental impacts, and potential additional demand for land.

The feedstocks in this study are treated as follows:

- Biogas produced via AD of bio-waste is accredited under Annex IX Part A. Biodegradable Garden and food waste is included under the definition for biowaste.
- Sewage sludge is also included as an advanced biofuels feedstock despite the recycling of sewage sludge being situated higher up the waste hierarchy. This highlights the misalignment between the WFD and the RED II Directive.
- The biogenic fraction of the MRW stream is accredited as a feedstock under Annex IX Part A.
- MSs can choose to include fuels derived from non-renewable waste streams, defined as RCF, in their transport targets. The feedstocks this may impact are mixed plastic waste and the fossil portion of MRW. However, the delegated act to clarify the criteria which RCF must meet is yet to be finalised and is due this year. This leaves some uncertainty around the contribution from the mixed plastic and MRW streams in meeting transport targets and therefore the demand for these types of fuels.

Fuel quality directive

The FQD is an obligation for automotive fuel suppliers to reduce the GHG intensity of transport fuels by at least 6 % by 2020 compared to 2010, as defined under Directive 2009/30/EC Article 7a. As long as sustainability criteria are met, wastes and residues can be used for the production of biofuels for which the FQD will apply. These wastes include waste vegetable or animal oil biodiesel, biogas from municipal organic waste as compressed natural gas, biogas from wet or dry manure as compressed natural gas. These wastes can only be counted towards the FQD if biofuel is produced with no net carbon emissions from land use change (*Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009*). This suggests that municipal biowaste, sewage sludge and the biogenic content in MRW may be supported under this directive for use in fuel production thereby promoting these WTF pathways. More clarification is needed to understand the support for RCFs in this directive to understand the effect on mixed plastic waste and the fossil part of MRW.

Sustainable finance taxonomy

For economic activities to be classed as environmentally sustainable and therefore eligible for financing, they must meet at least one of the environmental objectives, not significantly harm any other objective, and meet minimum safeguards. The environmental objectives include: climate change mitigation; climate change adaptation; sustainable use and protection of water and marine resources; circular economy, waste prevention and recycling; pollution prevention and control, and ecosystem protection. Biogas and biofuel production is considered to meet some of the environmental objectives listed which means there may be financial support for the WTF pathways with biogenic content. In addition, the potential for the waste sector to reduce emissions through replacement of virgin raw materials, including fossil-based products used in the transport sector, is recognised as a contribution to climate change mitigation. This suggests that the WTF pathways may be supported by the sustainable finance taxonomy; however, the regulation is still under review and is expected to apply from 1 January 2022.

European Union Emissions Trading System

The European Union Emissions Trading System (EU ETS) sets a cap on the total amount of GHG emissions from installations and aircraft operators, which is reduced over time to encourage a reduction in the total emissions. If companies are below the cap, they can receive emission allowances which can be traded with another company who needs to purchase more credits. There is a limit on the number of credits that can be bought to ensure the value is not lost. Companies can incur fines if they have not purchased enough emission allowances to cover all its emissions (*EU ETS handbook*). One of the industries covered in Phase One of the ETS is oil refineries, therefore it is likely that the ETS will apply to the WTF pathways. The emission allowances for oil refineries are dependent on the MS because each will have its own allocation method for this industry under the total emissions cap for Phase One. An increase in the EU ETS costs would have an impact on the plants producing the fuels via the WTF pathways. Biogenic emissions are not affected by this scheme, and it also does not require incineration of municipal waste to have GHG emission permits, meaning this policy does not encourage the diversion of waste away from incineration and possibly towards the WTF pathways.

Extended producer responsibility

EPR schemes are to be established for all single-use plastic products, including: food containers; packets and wrappers; beverage containers with capacity up to three litres; cups for beverages; lightweight plastic carrier bags; wet wipes; balloons, and tobacco products with filters. These schemes extend the contribution of the producer to the EoL costs of packaging materials, including collection and sorting. Economic incentives or regulations may be used to encourage waste holders to deliver their waste into separate collection systems. It is up to MSs to decide whether to implement the EPR through legislative or non-legislative measures, with some countries yet to introduce any measures. Examples of measures that MSs could take are deposit-refund schemes, encouraging design improvements to reduce the environmental impacts and to reduce the amount of waste generated during production. The Green Dot is an EPR scheme which is a trademark recognised by multiple countries, both within and outside of the EU. The purpose of the Green Dot is to inform customers that those producers have paid a financial contribution for the collection, sorting, and recovery of the packaging when it becomes waste (Packaging Recovery Organisation Europe, n.d.). These schemes encourage the collection of packaging waste which is likely to be diverted to recycling rather than for recovery, negatively impacting these WTF pathways.

Single-use plastic directive 2019/904

Directive 2019/904 on the reduction of the impact of certain plastic products on the environment includes targets for single-use plastic. In addition to the content of recycled plastic in PET bottles and collection targets for single-use plastic, this directive covers a range of other targets for the reduction, marketing, and composition of different single-use plastic products. Cups for beverages, including their covers and lids, and food containers are included in the reduction in consumption of single-use plastics by 2026 compared to 2022. Options for MSs to meet these targets put forward by the Commission include deposit-refund schemes and separate collection targets for relevant EPR schemes. The placement of cutlery; plates; beverage stirrers; expanded polystyrene food and beverage containers, as well as cotton bud sticks, straws, and sticks to support balloons, but with some exceptions, on the market is prohibited from 2021. Clear labelling on packaging is required to inform consumers of appropriate waste management options and of the presence of plastics in the product. This directive is unlikely to support the use of plastic waste in the WTF pathway because recycling is the key focus.

End of waste criteria

There are four main requirements for waste that has undergone a recovery operation to obtain the status of a product or a secondary material in the EoW criteria outlined in Article 6 of Directive 2008/98/EC. These cover the use of the product for specific purposes, the existence of a market or demand for that product, that technical requirements are met for the specific purposes along with the relevant legislation and standards, and the avoidance of adverse environmental or human health impacts resulting from product use. There are currently only three materials for which the EoW criteria have been established: glass cullet; copper scrap, and iron, steel, and aluminium scrap. Other materials listed in the directive that should have criteria developed include: construction and demolition waste; some ashes and slags; scrap metals; aggregates; tyres; textiles; compost; wastepaper, and glass. The relevance of the EoW criteria to the waste feedstocks in this report is therefore unclear, which has been identified as a knowledge gap.

ANNEX E
GLOSSARY OF ACRONYMS

Acronym	Definition
AD	anaerobic digestion
ASR	automotive shredder residue
CAPEX	capital expenditures
CCS	carbon capture and storage
CCSU	carbon capture, utilisation and storage
CDU	crude distillation unit
CNG	compressed natural gas
CTL	coal-to-liquids
DfT	Department for Transport
DHT	distillate hydrotreater
EfW	energy from waste
EoL	end of life
EoW	end of waste
EPR	extended producer responsibility
EU ETS	European Emissions Trading Scheme
FB	fluidised bed
FCC	fuel catalytic cracker
FQD	Fuel Quality Directive
FT	Fischer Tropsch
GHG	greenhouse gas
GTL	gas-to-liquid
HCK	hydrocracking
HDPE	high-density polyethylene
HDS	hydrodesulfurization
HTL	hydrothermal liquefaction
LCA	life cycle assessment
LDPE	low-density polyethylene
MRF	materials recovery facility
MRW	mixed residual waste
MS	member states
MSW	municipal solid waste
NHT	naphtha hydrotreater
OCM	oxidative coupling of methane
OPEX	operating expenditures
O&M	operational and maintenance

Acronym	Definition
PET	polyethylene terephthalate
PMMA	polymethyl methacrylate
PP	polypropylene
PS	polystyrene
PSA	pressure swing adsorption
PVC	polyvinyl chloride
RCF	recycled carbon fuels
RDF	refuse derived fuel
RED II	Renewable Energy Directive
RFNBO	Renewable Fuel from Non-Biological Origin
RTFO	Renewable Transport Fuel Obligation
SAF	Sustainable Aviation Fuels
SHDS	selective hydrodesulfurisation
TRL	technology readiness level
VGO	vacuum gas-oil
WFD	Waste Framework Directive
WRAP	Waste and Resources Action Programme
WTF	waste to fuel
WTP	waste to products

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