UKRI Interdisciplinary Centre for Circular Chemical Economy

Final Report

Non-Technical Challenges to Non-Mechanical Recycling

Project code: POS105
Research date: Oct 2021- April 2022 **Date:** April 2022

WRAP's vision is a world in which resources are used sustainably.

Our mission is to accelerate the move to a sustainable resource-efficient economy through re-inventing how we design, produce and sell products; re-thinking how we use and consume products; and re-defining what is possible through re-use and recycling.

Find out more at www.wrap.org.uk

The National Interdisciplinary Centre for the Circular Chemical Economy (CircularChem) brings together stakeholders from academia, industry, government, NGOs and general public to transform the UK's chemical industry into a fossil-independent, climate-positive and environmentally-friendly circular economy. As part of a £30 million strategic government investment it will play a key role in helping the UK to reduce waste and the environmental impacts of production and consumption and creating opportunities for new UK industries.

Find our more at www.circular-chemical.org

The work carried out in this report is supported by EPSRC under grant number EP/V011863/1.

Document reference (please use this reference when citing WRAP's work):
WRAP, 2021, Banbury, Non-Technical Challenges to Non-Mechanical Recycling, Prepared by Thomas Baker

Written by: Thomas Baker

Front cover photography: Coloured polymer pellets being poured from a glass test tube.

Executive summary

A high-level desk-based research study and series of stakeholder interviews has been conducted to ascertain the key non-technical challenges to the implementation of non-mechanical recycling in the UK, with particular emphasis on legislative elements. This work has been conducted to assist that of the UKRI National Interdisciplinary Centre for the Circular Chemical Economy (CircularChem) towards reducing UK synthetic/chemical derived waste, the environmental impacts of production and consumption, and to create opportunities for new UK industry development.

The non-mechanical (aka chemical) recycling sector is rapidly emerging and has the potential to support and complement current best practices in waste prevention and circularity, predominantly for plastics and the difficult to (mechanically) recycle category (films and flexibles). The definition of, and difference between, non-mechanical and chemical recycling is a discussion point itself. There is no formal, standardised definition that is widely accepted at all levels, despite broad similarities in current suggested definitions. Similarities and differences include the:

- exclusion of energy recovery,
- synonymous terminology use,
- chemical structure alteration,
- inputs as 'waste'; and,
- focus on included technologies, principles, or processes and their output

The current non-acceptance of a definition at a legally binding level extends into other areas. New recycling processes face economic, technical, legal, and environmental concerns before consideration of supporting infrastructure for further development. Seven key challenges have been identified with discussion surrounding these. The challenges (with recommendations) include the lack of:

1. **A legal and industry accepted formal, standardised definition.**
    a. A legal and industry accepted definition should be formalised between government and industry that factors in the current and potential future scope of chemical recycling (i.e. not linked to specific technologies), to best ensure that legislation referencing chemical recycling is accurate and applicable.
2. **Consideration and overall acceptance of chemical recycling in the recycling rank of the waste hierarchy – to end misclassification of chemical recycling.**
    a. Current legislation requires updating with an understanding, aided by the above, to the intentions of chemical recycling. Moreover, that separate operations (i.e. incineration) are actually treated separately and each are correctly placed in the waste hierarchy. Future legislation should continue to reflect this.
3. **Acceptance of an approach for allocating recycled content from chemically recycled substances that is consistent across jurisdictions.**
    a. Such a system requires development, with mass balance via non-mass-based calculations as the industry preferred mechanism. Mass balance is a currently utilised tool with UK governmental acceptance in other industries, with white papers suggesting a methodology for chemical recycling already published. This should apply across jurisdictions to enable trade and collaboration.
4. **Clarity on End of Waste legislation and synergy with UK (and EU/wider) REACH.**
    a. Different regulatory End of Waste regimes exist across the EU and UK that are not fully harmonised creating regulatory burden for compliance. Review and harmonisation of criteria for End of Waste, and on REACH for substances

produced, is invaluable to clarifying correct treatment of waste, material inputs, and outputs.

5. **Clarity on incoming policy (EPR, DRS, PPT, and Consistent Collections) towards funding allocation, waste feedstock segregation, which includes bale specifications from MRFs reducing quality of waste feedstocks.**
    a. A plethora of incoming policy will fundamentally change the UK waste management sector. This is not specific to chemical recycling but ultimately requires clarification of the minutiae for its applicability to chemical recycling given the prior challenges.
6. **Movement towards facilitated cross-chain collaboration and investment for growth (assisted by government) considering sensitive data sharing for private enterprise(s).**
    a. A lack of support for the industry was highlighted as a problem due to scant mention of chemical recycling in waste strategies across devolved nations. It is recommended that chemical recycling be incorporated into waste strategies and receive support for industry growth, cautioning that chemical recycling should not be overgeneralised as technologies can be disparate.
7. **Wider stakeholder understanding and approval of chemical recycling, and more broadly that of waste management in part due to poor transparency and reporting mechanisms.**
    a. As with any large complex system there are 'black box' elements to its working. It is recommended that, including the above clarity challenges, general waste management operations (i.e. waste movement, legislative 'bleed-in') are mapped before a focus on chemical recycling specifics are made and that this information is made available to improve transparency.

An additional but oft not mentioned component, though part of the cross-chain collaboration challenge, is the effect of upstream design and material choices. These can be implemented faster than new collection and labelling systems, legislative changes, and waste management strategies can cope with – curtailing efforts at improving recycling rates. The lack of clarity on current and incoming legislation was highlighted by stakeholders as a major impediment to investment as there is a severe lack of assurance on the financial stability over the next decade with phased policy implementation; complicated further as chemical recycling is new, innovative and disruptive relying heavily on plastics at a time of strong plastic push-back reflected in plastic-focused legislation. Facilitated discussion with government on these challenges, due as part of this body of work, was agreed upon as paramount for pursuing new waste management strategies such as chemical recycling.

The challenges are by no means exhaustive, all elements are systemically entwined with multiple feedback loops and unintended consequences outside just those listed. Recommendations are based on current evidence of the challenges and solutions already proposed. Mapping explicit mechanisms by which these challenges are associated is extremely difficult; regardless, readers are urged to consider each element, which are discussed separately here, as part of a whole for the challenges with implementing chemical recycling to a greater extent in a UK context.

Contents

1.0 Introduction 6
1.1 The Waste Hierarchy 6
1.2 Non-Mechanical Recycling Overview 9
1.3 Definition(s) for Chemical Recycling 9
2.0 Government Policy and Legislation 14
2.1 Current Policy 14
2.1.1 UK Waste Strategies 14
2.1.2 Incineration Classification 16
2.1.3 Food Safety 19
2.2 Mass Balance 21
2.2.1 Digital Technologies: Blockchain 24
2.3 End of Waste and REACH 24
2.4 Incoming Policy 28
3.0 Perception 30
4.0 UK Infrastructure and Investment 31
5.0 Conclusions 34

Glossary

AD	**A**naerobic **D**igestion
BPF	**B**ritish **P**lastics **F**ederation
CE	**C**ircular **E**conomy
CR	**C**hemical **R**ecycling
CTPA	**C**osmetic, **T**oiletry & **P**erfume **A**ssociation
DAERA	**D**epartment of **A**griculture, **E**nvironment and **R**ural **A**ffairs
DLT	**D**istributed **L**edger **T**echnology
DRS	**D**eposit **R**eturn **S**cheme
EFSA	**E**uropean **F**ood **S**afety **A**uthority
EfW	**E**nergy **f**rom **W**aste
EMF	**E**llen **M**acArthur **F**oundation
EoW	**E**nd **o**f **W**aste
EPR	**E**xtended **P**roducer **R**esponsibility
FCM	**F**ood **C**ontact **M**aterials
FDF	**F**ood & **D**rink **F**ederation
FSA	**F**ood **S**tandards **A**gency
IED	**I**ndustrial **E**missions **D**irective
LA	**L**ocal **A**uthority
LCA	**L**ife **C**ycle **A**ssessment
LHV	**L**ower **H**eating **V**alue
MR	**M**echanical **R**ecycling
MRF	**M**aterials **R**ecycling **F**acility
NIMBY	**N**ot **I**n **M**y **B**ack **Y**ard
NMR	**N**on-**M**echanical **R**ecycling
PPT	**P**lastic **P**ackaging **T**ax
PRF	**P**lastics **R**ecycling **F**acility
rWFD	**R**evised **W**aste **F**ramework **D**irective
WID	**W**aste **I**ncineration **D**irective
WQP	**W**aste **Q**uality **P**rotocol

Acknowledgements

The author would like to thank the following for their contributions:
Helen Jordan (BPF); Carlos Ludlow-Palafox (Enval); Sally Beken (KTN); Aad van Moorsel, Samantha Finnigan, and Han Wu (Newcastle University); Cloé Ragot (Plastic Energy); Adrian Whyle (Plastics Europe); Bill Elliott (Quantafuel); Stuart Morgan (RECOUP); Elena Parisi and Sophie Gilham (Recycling Technologies Ltd.); Geoff Brighty (ReNew ELP); Paul Davidson (UKRI); Michael Shaver (University of Manchester).

1.0 Introduction

Non-mechanical recycling has an important role to play in helping the UK Plastics Pact reach its targets, specifically Target 3: '70% of plastic packaging effectively recycled or composted by 2025' and Target 4: '30% average recycled content across all plastic packaging by 2025' – in line with the Plastic Packaging Tax[1], taking effect in April 2022. Further, new incoming legislation will affect the UK recycling sector and efforts towards zero avoidable waste by 2050 and eliminating avoidable plastic waste by end of 2042.

WRAP has been commissioned by the UKRI Interdisciplinary Centre for Circular Chemical Economy to investigate the key non-technical impediments to the implementation of circular chemical economy and to create an action plan/roadmap to address them. The primary focus will be on non-mechanical recycling (chemical recycling). Technical difficulties with chemical recycling (CR) processes are outside the scope of this report.

1.1 The Waste Hierarchy

The Waste Hierarchy[2], as initially set out in article 4 of the revised Waste Framework Directive[3], "ranks waste management options according to what is best for the environment." With waste defined as (Chapter 1, Article 3):

> '"*any substance or object which the holder discards or intends or is required to discard*"

Deviation from the hierarchy is permissible if justified by life-cycle thinking as to the overall impact when managing the specific waste. Other considerations, such as "precaution and sustainability, technical feasibility and economic viability, protection of resources as well as the overall environmental, human health, economic and social impacts" can also be accounted for. The Waste Hierarchy Guidance document (published 2011) provides additional detail for its implementation and breaks this down into material groups. For plastics, the list is as follows:

- Prevention,
- Preparation for re-use,
- Closed loop recycling,
- Other recycling,

---

[1] *Plastic packaging tax - gov.uk*

[2] *Waste hierarchy evidence summary - gov.uk*;

Waste hierarchy guidance - gov.uk

[3] *Directive 2008/98/EC on waste and repealing certain Directives Article 4(1) - gov.uk*

- Energy recovery[4]; and,
- Disposal.

Closed loop recycling refers to when an item is recycled into the same product, i.e. A-to-A, with open loop being A-to-B. No specific mention is made to chemical or mechanical recycling (MR) in the waste hierarchy guidance; however, recycling is used as a standalone term to refer to mechanical methods.

Several organisations[5] have expressed desire for chemical recycling to be included more definitively in the plastics waste hierarchy (see example Figure 1) as it can form new recycling-based solutions to improving plastic circularity, and more broadly that of polymers/chemicals; noting that this should not undermine more preferrable waste solutions (prevention, re-use, and mechanical recycling). The proposed placement of MR and CR is reflective of energy requirements, emissions, and other factors from reviewed LCA data[6] in accordance with ISO 14040 guidelines. Stakeholders expressed that waste management strategy conclusions from LCA data alone were often used poorly and prematurely, dismissing CR completely rather than as a complement to current practices to improve circularity by developing technologies. It was argued that CR is a complement to MR (see section 3.0 Perception) and a preferred waste management option over incineration for reduced environment impact. Note that such statements ultimately require more data and are highly dependent on specific processes, inputs, locations, and other factors. Moreover, there is a lack of LCA method standardisation and implementation for LCAs to be directly compared[7].

[4] Note to energy recovery in guidance document: "'energy recovery' covers a range of technologies, some of which will be more environmentally beneficial than others. Future versions will differentiate between technologies as more scientific evidence becomes available."

[5] Fixing the system - Green Alliance;

Chemical Recycling and Recovery - Zero Waste Europe

[6] The Plastics Waste Hierarchy: A review of plastic waste management practices, life cycle assessments, challenges and opportunities - WRAP

[7] Alhazmi, H.; Almansour, F.H.; Aldhafeeri, Z. Plastic Waste Management: A Review of Existing Life Cycle Assessment Studies. Sustainability 2021, 13, 5340. https://doi.org/10.3390/su13105340

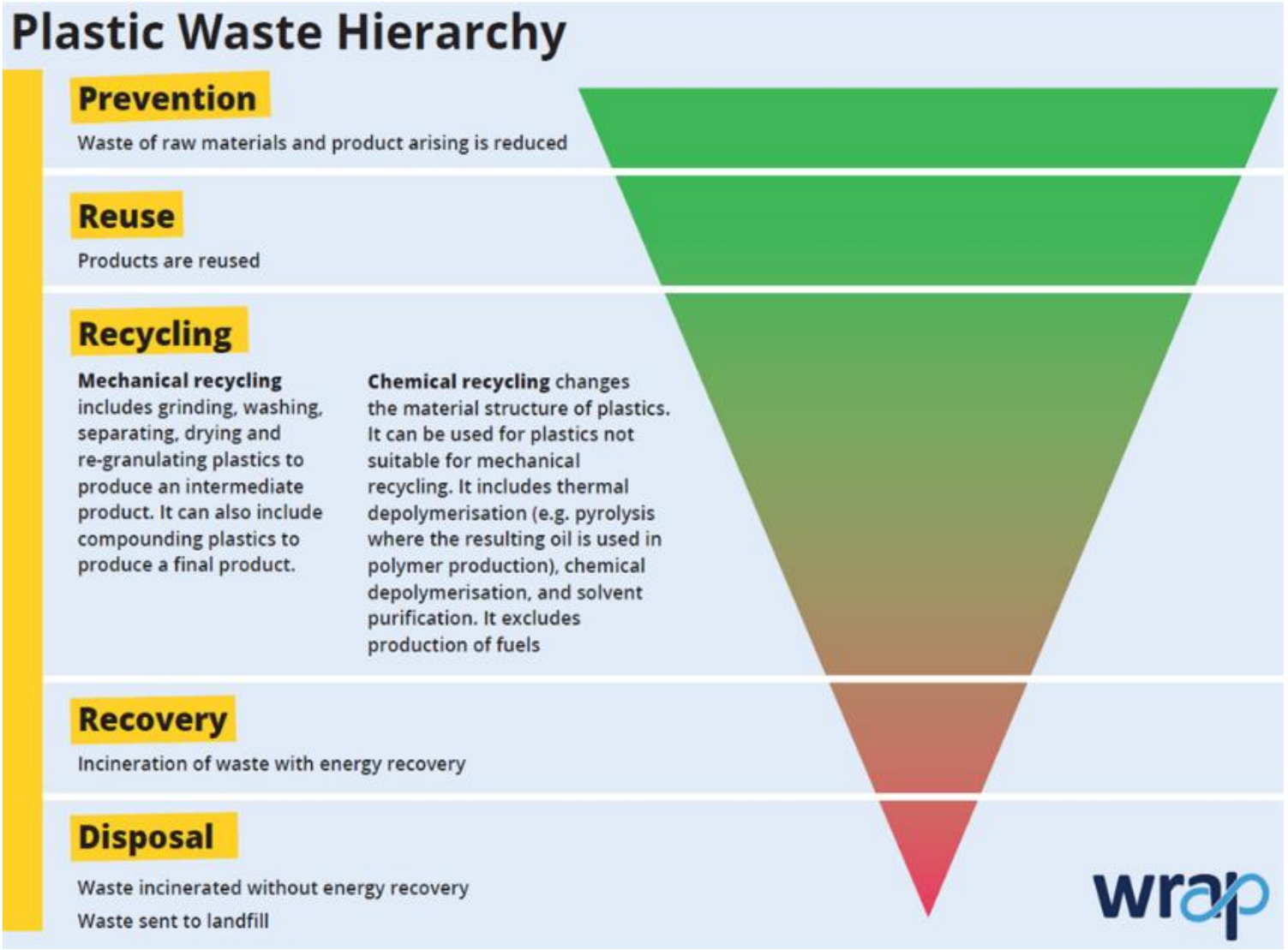


Figure 1: Alteration to traditional waste hierarchy specific to plastics, including chemical recycling

1.2 Non-Mechanical Recycling Overview

Non-mechanical recycling (NMR), herein synonymous with chemical recycling (CR), is a broad term describing a range of waste management technologies that have the potential to support and complement current recycling methods in the circularisation of plastics and other materials/substances. CR is not limited to plastics, though they are often the primary focus, particularly the 'difficult to recycle' group, such as films or laminates. Difficult to recycle here pertains to mechanical recycling.

Traditionally, or most commonly, CR technologies are grouped into four main categories[8]. Other technologies, such as hydrothermal (i.e. supercritical water), are being developed beyond the below groupings:

1. **Pyrolysis** – thermal breakdown of material without oxygen, resulting in a range of hydrocarbon products including wax, oil and gas. The gas is often burnt to provide energy to the process, whereas the oil and wax can be sold.
2. **Gasification** – partial combustion of material to produce carbon monoxide (CO) and hydrogen (H_2), which is a mixture known as SynGas. This gas can be burnt for energy or used in the production of new hydrocarbons.
3. **Chemical depolymerisation** – use of chemicals and catalysts to selectively breakdown a polymer into its monomers or intermediate units.
4. **Dissolution** – polymers are dissolved in selected solvent(s) so the polymers can be separated from any contamination before precipitation for re-use as a polymer. Dissolution does not affect the chemical structure of the polymer.

Thus, the principle of CR is conversion of the chemical structure (of long chain hydrocarbon molecules) into constituent parts which can then be reformed into the original (or differing) hydrocarbons, enabling the creation of new, virgin quality material. Pyrolysis is perhaps the most utilised technology currently. A previous WRAP report on the Non-Mechanical Recycling of Plastics discussing the technological aspects is available online[9].

The technologies listed above are not finite and their application can differ depending on waste input. Generalisations to chemical recycling based on a single technology is not recommended, with case-by-case evaluation suggested.

1.3 Definition(s) for Chemical Recycling

Recycling, as defined by the revised Waste Framework Directive[10], is interpreted as:

> *"any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations"*

This broad definition is used to set the boundaries for recycling processes and explicitly excludes any that pertain to energy recovery operations. It was evident from stakeholder interviews and various literature that there are inconsistencies in the specific definition of chemical recycling

[8] *Note: the definition of chemical recycling and inclusion/exclusion criteria will be discussed in section 0.*

[9] Non-mechanical recycling of plastic - WRAP

[10] Directive 2008/98/EC on waste and repealing certain Directives Article 3(17)- gov.uk

occurring at organisational, industry body, and national/international governmental levels[11]. Moreover, the lack of terminology clarity and consistency creates issues in understanding the potential that various chemical recycling technologies can offer a circular economy and how legislation ought apply. This inconsistency was highlighted as an issue that, among other problems, fed a misinformed perception of what chemical recycling is, such as the general public's fear of 'chemical'. Some organisations[12] have called for the term chemical recovery (polymer to molecule) to be used in legislation to differentiate from chemical recycling (polymer to monomer or oligomer). Differentiation of such terms adds additional complexity to standardising definitions and processes, prior to potential acceptance in the waste framework and guidance on implementation.

[11] *Chemical Recycling of Polymeric Materials from Waste in the Circular Economy - European Chemicals Agency*

[12] *Chemical Recycling and Recovery - Zero Waste Europe*

Table 1 lists select definitions for chemical recycling from various organisations. While broadly similar in their scope key differences remain, namely:

- specification on exclusion of energy recovery,
- synonymous use of 'feedstock' and 'chemical',
- reference to inputs (plastics) being 'waste',
- use of 'polymer' and/or 'plastic'; and,
- focus on included technologies, principles, or processes and their output.

From stakeholder interviews the definition put forward by The European Coalition for Chemical Recycling was the most well received as it defines based on principles rather than technologies, excludes products used for energy recovery, and uses the broader category of 'polymer' to capture all applicable substances, despite some polymers not being suitable for particular CR technologies/operations. Moreover, it stipulates that the process will alter the chemical structure, unlike MR where the aim is preservation of molecular backbone. This stipulation allows other novel technologies, such as bio-chemical (enzymatic) recycling[13], to be included as depolymerisation (see section 2.1.3 Food Safety for discussion of depolymerisation) is the primary operation. As technologies will change between processes and evolve with further developments definitions should focus on the principle that outputs are materially circular than any specific technological processes. One stakeholder proposed the term 'molecular stewardship' for the retention of responsibility of the chemical substances produced in the process, this will factor into discussions on mass balance and blockchain in section 2.2.

Stakeholders were very forthcoming that any definition should be explicit in its exclusion of energy recovery or fuel production. Energy recovery may form part of the overall process in certain technologies, though does not constitute the recycling process; meaning that definitions should be primarily made based on outputs and not processes, as the process may produce both energy and substances (see commentary on Anaerobic Digestion in section 2.3: End of Waste and REACH). This statement is agreed upon by several organisations and was a recommendation put forth by The Rethink Plastic alliance, ECOS, Health Care Without Harm (HEAL), European Environmental Bureau (EEB) and Zero Waste Europe in a 2020 joint statement[14]. Classification of CR plants as incinerators will be discussed in section 2.1.2 Incineration Classification.

Feedstock was used variably to mean the waste feedstock input and the product output (that then becomes a feedstock for another process). This was highlighted as an area where consistent terminology would greatly improve clarity, particularly with End of Waste (discussed in section 2.3). Advanced recycling is another term used in place of chemical recycling though confusion occurs as the term can also be used to describe new technologies in mechanical recycling processes, such as artificial intelligence for optical sorting.

Mixed use of the terms 'polymer' and 'plastic' is made often within a waste context. Sole use of 'plastic' was somewhat contentious due to its own specific definition and how it could exclude elastomers, thermosets[15], or other materials that chemical recycling technologies may be able to handle as technology and industry continue to develop. Furthermore, use of 'polymer' may exclude some target chemicals and include the likes of non-target materials such as cellulose or lignin. Use of 'synthetic' may assist the definition, such as "synthetic polymers or chemicals of renewable or non-renewable origin", to also incorporate any instances of bio-based or bio-degradable synthetic substances (i.e. polyethylene and bio-polyethylene, or polylactic acid)

[13] *The Centre for Enzyme Innovation - University of Portsmouth*

[14] *Joint Statement. Chemical Recycling: 7 Steps to Effectively Legislate on Chemical Recycling*

[15] *Getting it right from the start: Developing a circular economy for novel materials - Green Alliance*

capable of being chemically recycled[16]. With efforts towards a circular chemical economy demarcation for inclusion/exclusion must be stipulated.

No (selected) definition makes direct reference to dissolution. Those that define based on the principle of chemical alteration would exclude dissolution as there is retention of polymer architecture, i.e., that no alteration to chemical structure or molecular weight should occur. Consequently, many stakeholders argued that this would make dissolution a form of mechanical recycling so should not be considered formally in CR. The British Plastics Federation Recycling Roadmap[17] put forward that dissolution is not CR, but a purification process under a broader NMR definition than in this report (not synonymous with CR).

Without a formal, standardised, consistent, and accepted definition across the value chain the boundaries for chemical recycling remain vague. This has direct and indirect effects on waste and circular economy strategies, End of Waste, plant classification (i.e. incinerators), recycled content targets, and other areas that will be discussed herein. It is cautioned that, even with a broad definition of chemical recycling, this should not be 'broad-stroke' applied in all instances. Harmonisation for reference is valuable but as technologies can be disparate, they should still be reviewed on a case-by-case basis[18].

---

[16] *Siracusa, V.; Blanco, I. Bio-Polyethylene (Bio-PE), Bio-Polypropylene (Bio-PP) and Bio-Poly(ethylene terephthalate) (Bio-PET): Recent Developments in Bio-Based Polymers Analogous to Petroleum-Derived Ones for Packaging and Engineering Applications. Polymers 2020, 12, 1641. https://doi.org/10.3390/polym12081641*

Niaounakis, M. Recycling of Biopolymers – The Patent Perspective. Eur. Polym. J. 2019, 114 (February), 464–475. https://doi.org/10.1016/j.eurpolymj.2019.02.027

[17] *Recycling Roadmap - BPF*

[18] *Chemical Recycling of Polymeric Materials from Waste in the Circular Economy - European Chemicals Agency*

Table 1: Select definitions for chemical recycling

Origin	Chemical Recycling Definition
British Plastics Federation	broad term used to describe a range of emerging technologies in the waste management industry which allow plastics to be recycled, that are difficult or uneconomic to recycle mechanically.
The European Coalition for Chemical Recycling	converts polymeric waste by changing its chemical structure to produce substances that are used as products or as raw materials for the manufacturing of products. Products exclude those used as fuels or to generate energy
ISO 472: 2013: 2.1690 Plastics – Vocabulary	<recycling of plastics waste> conversion to monomer or production of new raw materials by changing the chemical structure of plastics waste through cracking, gasification or depolymerization, excluding energy recovery and incineration *Note 1 to entry: "Feedstock recycling" and "chemical recycling" are synonyms.*
Defra - Our waste, our resources: a strategy for England	a family of treatment technologies where waste plastic is chemically treated in a way that recovers the base chemical constituents of which it is made
European Commission: A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions	any reprocessing technology using chemical agents or processes that directly affect either the formulation of the plastic or the polymer itself
The Ellen MacArthur Foundation - The New Plastics Economy: Rethinking the future of plastics	breaks down polymers into individual monomers or other hydrocarbon products that can then serve as building blocks or feedstock to produce polymers again.

2.0 Government Policy and Legislation

2.1 Current Policy

2.1.1 UK Waste Strategies

Strategies for England[19], Wales[20], Scotland[21], and Northern Ireland[22] are broadly aligned. Note that DAERA documentation is dated 2015, with a new Waste Management Strategy to be published in 2023[23]; draft consultations closed on the January 18th, 2022[24].

No explicit mention of chemical recycling is made in any documentation, however, the waste and resources strategy for England[25], published 2018, includes only a definition of CR amounting to one third of a page in the 146-page document. Other technologies, such as gasification and pyrolysis, are mentioned within the context of energy from waste towards increasing EfW efficiency prior to 2050. Conversely, the Welsh strategy is to place a "moratorium on any future large-scale energy from waste developments"[26] while they also "strive to achieve the highest rates of recycling in the world" – demonstrating the different strategic focuses across devolved nations. This includes the development of additional infrastructure to collect and recycle materials such as plastic film and rigid non-packaging plastic – the target materials for CR.

Research by Defra on waste trajectories to 2050[27] under four scenarios (ranging from unlimited wastefulness to a national adoption of strong environmental behaviours and legislation) forecast the percentage of waste sent to EfW to range from 12% to 21% (base year 2007 with 9% of waste sent to EfW). Stakeholder interviews largely saw EfW as a transient technology to be surpassed by CR for resource circularity, with more standardised LCAs required to conclude this; however, it should be noted that LCAs are not panacea for such determination. In this view came the barrier of chemical recycling plants being classified as incinerators. Such classification implies a different form of technology application with no element of circularisation involved and it being transient – phased out in the future rather than grown.

In January 2018 the 25 Year Environment Plan was published by HM Government setting out the goals and targets towards helping "the natural world regain and retain good health." Within this plan are the goals for minimising waste and managing chemical exposure (see below) that state the ambition of eliminating avoidable[28] plastic waste and to have negligible chemical emissions to the environment.

---

[19] *25-year-environment-plan - gov.uk*

[20] *Beyond Recycling - gov.wales*

[21] *Scotland's Zero Waste Plan - gov.scot*

[22] *Delivering Resource Efficiency: Northern Ireland Waste Management Strategy - daera-ni.gov.uk*

[23] *Northern Ireland consults on 'first ever' environment strategy - letsrecycle.com*

[24] *Draft Environment Strategy for Northern Ireland - nidirect.gov.uk*

[25] *Our waste, our resources: a strategy for England - gov.uk*

[26] *Beyond Recycling: A strategy to make the circular economy in Wales a reality - gov.wales*

[27] *Waste trajectories technical summaries - gov.uk*

[28] *Avoidable, as defined in the documentation: "We talk about plastic waste being 'avoidable' when the plastic could have been reused or recycled; when a reusable or recyclable alternative could have been used instead; or when it could have been composted or biodegraded in the open environment."*

25 Year Environment Plan – select goals

Goal 8: Minimising waste

We will minimise waste, reuse materials as much as we can and manage materials at the end of their life to minimise the impact on the environment. We will do this by:

- Working towards our ambition of zero avoidable waste by 2050
- Working to a target of eliminating avoidable plastic waste by end of 2042*.
- Meeting all existing waste targets – including those on landfill, reuse and recycling – and developing ambitious new future targets and milestones.
- Seeking to eliminate waste crime and illegal waste sites over the lifetime of this Plan, prioritising those of highest risk. Delivering a substantial reduction in litter and littering behaviour.
- Significantly reducing and where possible preventing all kinds of marine plastic pollution – in particular material that came originally from land.

**Avoidable means what is Technically, Environmentally and Economically Practicable.*

Goal 9: Managing exposure to chemicals

We will make sure that chemicals are safely used and managed, and that the levels of harmful chemicals entering the environment (including through agriculture) are significantly reduced. We will do this by:

- Seeking in particular to eliminate the use of Polychlorinated Biphenyls (PCBs) by 2025, in line with our commitments under the Stockholm Convention.
- Reducing land-based emissions of mercury to air and water by 50% by 2030.
- Substantially increasing the amount of Persistent Organic Pollutants (POPs) material being destroyed or irreversibly transformed by 2030, to make sure there are negligible emissions to the environment.
- Fulfilling our commitments under the Stockholm Convention as outlined in the UK's most recent National Implementation Plan.

In December 2018 the Resources and waste strategy for England[29] was published. Chapter 3 sets out the commitments that pertain to resources and waste (see below). Consistent Collection for all local authorities is expected to begin from October 2023, however, plastic films would be phased in with an 'end date' of financial year 2026/27[30] (discussed in section 2.4 Incoming Policy).

Resources and waste strategy for England, Chapter 3: Recovering Resources and Managing Waste

- improve recycling rates by ensuring a consistent set of dry recyclable materials is collected from all households and businesses
- reduce greenhouse gas emissions from landfill by ensuring that every householder and appropriate businesses have a weekly separate food waste collection, subject to consultation
- improve urban recycling rates, working with business and local authorities
- improve working arrangements and performance between local authorities
- drive greater efficiency of Energy from Waste (EfW) plants
- address information barriers to the use of secondary materials
- encourage waste producers and managers to implement the waste hierarchy in respect to hazardous waste

[29] *Our waste, our resources: a strategy for England - gov.uk*

[30] *Consultation on Consistency in Household and Business Recycling in England - gov.uk*

2.1.2 Incineration Classification

The Industrial Emissions Directive (IED) of the European Union[31] has been previously transposed into UK law[32] (England and Wales[33], Scotland[34], Northern Ireland[35]). The IED applies to waste and non-waste substances, both hazardous and non-hazardous. Facility classification is based on the treatment of inputs (see definitions below), that being if those produced or those entering are incinerated for energy they "must be regarded as an incineration plant." There are special provisions (see Chapter IV) to this such as the classification applying even if co-incineration occurs for just some of the output substances. As a result, the definition has been criticised as incorrect for the chemical recycling processes which are less suitably defined (section 1.3: Definition(s) for Chemical Recycling). This challenge was seen as a legacy position continuation as the IED was a replacement for the Waste Incineration Directive[36].

If the final substance is "still a waste and not a product" then Chapter IV of the IED (Special Provisions for Waste Incineration Plants and Waste Co-Incineration Plants) applies, following Defra guidance in Figure 2. Therefore, this has implications for End of Waste (section 2.3 End of Waste and REACH). Additional uncertainties arise that depend on the specific definition of 'process' (where one ends and another begins) and if such operations occur within the same or separate (co-)plants, thereby requiring separate permits.

Due to this misattribution planning and permitting can be misaligned, incurring additional administration and subsequent issues with public perception, financial costing, and specifically adherence to the relevant regulatory requirements. Assuming substances are still classified as waste the above is in opposition to the proposed definitions for CR as put forth in section 1.3 and for placement in the Waste Hierarchy (section 1.1), which specifically exclude energy recovery from chemical recycling definitions. That being, the processes should be treated as separate and complementary waste management processes, chemical recycling *and* incineration, rather than classified as only and wholly (co-)incineration. This follows the same premise that substances sent to a MRF then transferred to an incineration plant, instead of mechanical recycling, does not classify the MRF as a (co-)incineration plant – regardless of the facilities proximity to one another.

Without acceptance of the substance's potential for circularisation into 'new' virgin-quality materials operations become geared towards other routes of financial security (such as greater energy recovery) thereby inhibiting resource circularity from the process and harming initial perception of the technologies. If materials derived from such substances were accepted as recycled content, there is potential for market signalling to begin procurement, thus enabling a method for sector growth and new circular markets. This scenario is dependent on an acceptable method for allocating recycled content, one possibility is the mass balance approach.

---

[31] *Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control)*

[32] *Industrial emissions standards and best available techniques - gov.uk*

[33] *The Environmental Permitting (England and Wales) (Amendment) Regulations 2013 - legislation.gov.uk*

[34] *The Pollution Prevention and Control (Scotland) Regulations 2012 - legislation.gov.uk*

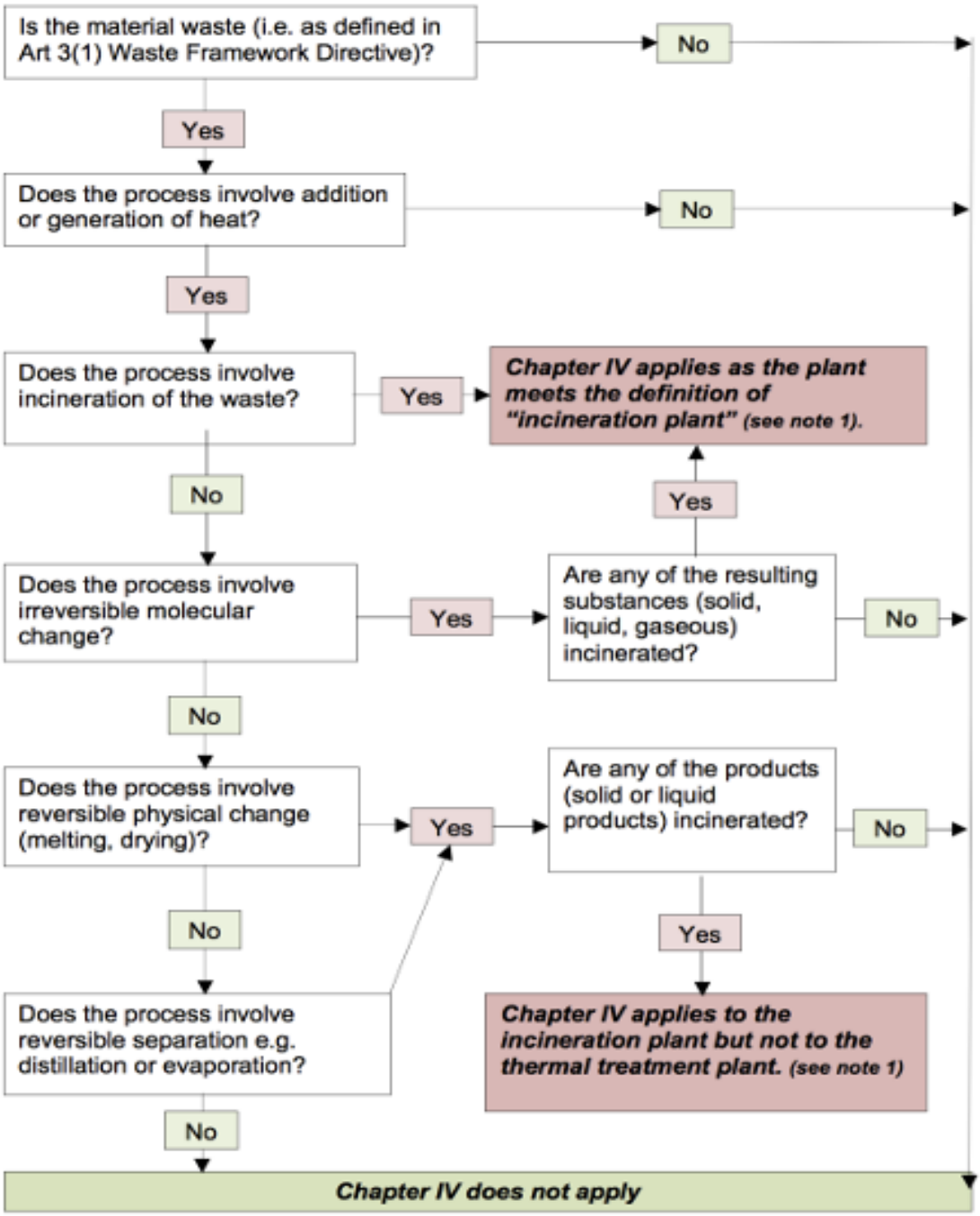
[35] *The Pollution Prevention and Control (Industrial Emissions) Regulations (Northern Ireland) 2013 - legislation.gov.uk*

[36] *Industrial Emissions - Environment - European Commission*;

The Waste Incineration Directive - Environment - European Commission

Directive 2010/75/EU – Chapter 1, Article 3, Definitions (40-41)
"(40) 'waste incineration plant' means any stationary or mobile technical unit and equipment dedicated to the thermal treatment of waste**, with or without recovery of the combustion heat generated, through the incineration by** oxidation of waste as well as **other thermal treatment processes, such as pyrolysis, gasification** or plasma process, if the substances resulting from the treatment are subsequently incinerated; **(41) 'waste co-incineration plant' means** any stationary or mobile technical unit whose main purpose is the generation of energy or production of material products and which uses waste as a regular or additional fuel or in which waste is thermally treated for the purpose of disposal through the incineration by oxidation of waste as well as **other thermal treatment processes, such as pyrolysis, gasification** or plasma process, if the substances resulting from the treatment are subsequently incinerated;"

Directive 2010/75/EU – Chapter 5: Waste Management: Section 5.1: Incineration and Co-incineration of Waste: Interpretation of Section 5.1
If co-incineration takes place in such a way that the **main purpose of the plant is not the generation of energy** or production of material products **but rather the thermal treatment of waste**, the **plant must be regarded as an incineration plant**.



Note 1: Chapter IV of the IED only applies if the substance burned is still a waste and not a product

Figure 2: Defra Environmental permitting guidance: waste incineration; Section 7.2 Check if the process uses thermal treatment[37]

[37] Environmental permitting guidance: waste incineration 2015 - gov.uk

2.1.3 Food Safety

Food safety is an important consideration given the potential for large end markets of CR produced packaging materials, with over 2.2 million tonnes of plastic food packaging placed on the market each year in the UK[38]. There are multiple regulations across the UK and EU that concern Food Contact Materials (FCMs), though application to CR is unclear or not specific, but in consideration. FCMs are regulated under Commission Regulation (EC) 1935/2004[39] which gives general safety requirements (such as that under normal conditions FCMs do not transfer substances which could endanger human health – see Article 3: 1). This also states that such FCM should "be manufactured in compliance with good manufacturing practice". This is set out in Commission Regulation (EC) 2023/2006 (on good manufacturing practice for materials and articles intended to come into contact with food)[40]. Commission Regulation 10/2011 (EU) is a "specific measure within the meaning of Article 5 of Regulation (EC) 1935/2004" on plastic intended to come into contact with food[41]. This applies only to virgin plastics and substances therein that may migrate to food, with food safety authority oversight of said substances. The Food Standards Agency (FSA) is the UK body responsible for overseeing this regulation, the European Food Safety Authority (EFSA) is the equivalent for the EU. Commission Regulation (EC) 282/2008 on recycled plastic in contact with foods was transferred to UK legislation[42] after Brexit. Relevant regulatory quotes on scope and contamination testing applicable to CR are shown in the box below.

Commission Regulation (EC) No 282/2008

Introduction, 6:

"Plastic waste can be treated mechanically to produce recycled materials and articles or it can be broken down to monomers and oligomers by chemical depolymerisation. Monomers and oligomers resulting from chemical depolymerisation should not be treated differently from monomers manufactured by chemical synthesis. Therefore, they are covered by the authorisation of monomers and additives in Directive 2002/72/EC and they should comply with the specifications and purity criteria established therein. Therefore, they should not be covered by this Regulation."

Article 1 Subject matter and scope, 2a:

"2. This Regulation shall not apply to the following recycled plastic materials and articles, provided that they have been manufactured according to good manufacturing practice, as laid down in Regulation (EC) No 2023/2006:

a) recycled plastic materials and articles made with monomers and starting substances, derived from chemical depolymerization of plastic materials and articles;"

Article 2 Definitions, 2d:

"'challenge test' means a demonstration of the effectiveness of a recycling process to remove chemical contamination from plastic materials or articles;"

[38] POSTNOTE No. 605, July 2019. Plastic Food Packaging Waste - parliament.uk

[39] Commission Regulation (EC) No. 1935/2004 of 27 October 2004 on materials and articles intended to come into contact with food and repealing Directives 80/590/EEC and 89/109/EEC - legislation.gov.uk

[40] Commission Regulation (EC) No. 2023/2006 of 22 December 2006 on good manufacturing practice for materials and articles intended to come into contact with food (Text with EEA relevance) - legislation.gov.uk

[41] Commission Regulation (EU) No. 10/2011 of 14 January 2011 on plastic materials and articles intended to come into contact with food (Text with EEA relevance) - legislation.gov.uk

[42] Commission Regulation (EC) No. 282/2008 of 27 March 2008 on recycled plastic materials and articles intended to come into contact with foods and amending Regulation (EC) No 2023/2006 (Text with EEA relevance) - legislation.gov.uk

The above pertains only to MR plastic materials, with plastic materials and articles derived after "chemical depolymerisation" not applicable to said legislation. However, chemical depolymerisation is not specifically defined within this legislation leaving interpretation relatively open. Article 2: 2d relies on demonstration of chemical contamination removal; considering that CR technologies can in principle meet this requirement there is potential for (future) acceptance (in accordance with Commission Regulation (EC) 1935/2004[43]). Instead, Commission Regulation (EU) 10/2011[44] and Commission Regulation (EC) 2023/2006[45] should be applicable; where polymer is defined as per the box below, in which substances derived from CR technologies could also be interpreted as acceptable – pending suitability with other regulatory components.

Commission Regulation (EU) No N10/2011

Article 3 Definitions

(3) 'polymer' means any macromolecular substance obtained by:

(a) a polymerisation process such as polyaddition or polycondensation, or by any other similar process of monomers and other starting substances; or

(b) chemical modification of natural or synthetic macromolecules; or

(c) microbial fermentation;

In December 2021 EFSA announced that 282/2008 will be repealed, and that new regulation is under preparation[46], stating:

"Presently, recycled plastic may be placed on the market subject to National rules, but the Regulation requires the Commission to decide on the authorisation of suitable recycling processes following the publication of EFSA opinions on their ability to manufacture safe recycled plastic."

The new scope was stated as "essentially all recycling processes". Moreover, in an EC webinar[47] (December 2021) the above exemption was restated with additional information regarding accordance of use and interpretation, as below. Slide 53 *appears* to give 'allowance' to partially depolymerised substances.

EC Webinar explaining draft Regulation on Recycled Plastic FCM

Slide 19: Regulation (EC) No 282/2008

The Regulation exempts:

Chemical depolymerisation, Off-cuts and scraps, barrier layers

these may be used in accordance with Regulation (EU) 10/2011

Slide 53: What happens with the following technologies

Chemical depolymerisation → only complete depolymerisation into monomers exempted

(today, as chemical depolymerisation is undefined, partial depolymerisation seems 'allowed')

[43] Commission Regulation (EC) No. 1935/2004 of 27 October 2004 on materials and articles intended to come into contact with food and repealing Directives 80/590/EEC and 89/109/EEC - legislation.gov.uk

[44] Commission Regulation (EU) No. 10/2011 of 14 January 2011 on plastic materials and articles intended to come into contact with food (Text with EEA relevance) - legislation.gov.uk

[45] Commission Regulation (EC) No. 2023/2006 of 22 December 2006 on good manufacturing practice for materials and articles intended to come into contact with food (Text with EEA relevance) - legislation.gov.uk

[46] Specific EU policy initiatives. Evaluation and revision of EU rules on FCMs - europa.eu

[47] Webinar explaining draft Regulation on Recycled Plastic FCM 16 December 2020 - europa.eu

As regulations are under review (with the current state only *potentially* applicable) and are now separate to those of the EC, chemical depolymerisation is undefined, and future alignment between FSA and EFSA is unknown – the status is rather ambiguous. However, it does seem to imply Regulation (EU) No 10/2011 applicability and that CR technologies are being considered.

Section note: The information here does not represent a final position nor commitment from the European Commission. Information is under validation or preliminary and cannot be guaranteed. Only the Court of Justice of the European Union is competent to authoritatively interpret Union law.

2.2 Mass Balance

Mass balance is an industry proposed mechanism for tracing CR substances. The mass balance approach relies on recycled feedstock replacing the equivalent virgin feedstock at the beginning of the value chain – which is then able to be allocated to the product, in a way where input and output match. Its basis is in the conservation of mass, though method of measurement does not necessarily use mass as it can be difficult or impossible to directly measure. This is true of CR substances as they are indistinguishable from identical substances of other origin (i.e. direct fossil derivation). The premise of 'molecular stewardship' (i.e. traceability) is therefore a difficult to implement without a means to track substance movement in some form. For mechanical recycling this is achieved on a 'per mass' basis, which is supported by the ISO definition[48] for "recycled content" (see box below).

BS EN ISO 14021:2016+A1:2021 "recycled content" definition

"Proportion, by mass, of recycled material in a product or packaging. Only pre-consumer and post-consumer materials shall be considered as recycled content, consistent with the following usage of the terms:

Pre-consumer material:
Material diverted from the waste stream during a manufacturing process. Excluded is reutilization of materials such as rework, regrind or scrap generated in a process and capable of being reclaimed within the same process that generated it.

Post-consumer material:
Material generated by households or by commercial, industrial and institutional facilities in their role as end-users of the product, which can no longer be used for its intended purpose. This includes returns of material from the distribution chain."

Furthermore, food or other controlled use applications are important considerations due to current regulatory controls on material use (food is discussed in section 2.1.3). However, no such implementation model is currently accepted at a governmental level and reticence on this front has been highlighted as an impediment to chemical recycling being accepted as a valued part of the recycling value chain. Particular concern was again drawn to the Plastic Packaging Tax coming into force in April of 2022 – leaving many worried about meeting a 30% recycled content across packaging and other areas. It was put forward that small or medium-sized enterprises (SMEs) may be disadvantaged when competing with large enterprises who will have the financial capital to procure recyclate.

There is no method to directly measure by mass the recycled content from CR in a mixed source product; therefore, the mass balance approach could be an acceptable method for recycled content determination in chemically recycled substances. However, the calculation used must

[48] BS EN ISO 14021:2016 Environmental labels and declarations. Self-declared environmental claims (Type II environmental labelling)

fairly distribute the allocation. A white paper[49] produced by the Ellen MacArthur Foundation (EMF) on mass balance (supported by the BPF[50]) for a circular chemical economy put forward three potential options: mass allocation, carbon counting, and net calorific value (aka Lower Heating Value – LHV).

Mass allocation relies on substances being of essentially identical composition and allocation on a proportional basis (i.e. 60% raw material from CR would be 60% recycled content, regardless of process losses). However, there is heterogeneity of resin type, grade, and additive inclusion (for plastics); as fossil feedstock is predominantly carbon and hydrogen the introduction of nitrogen, oxygen, chlorine, salts and minerals, glass fibres, etc. (termed ballast) may occur. As these are to be removed from the recycling process, they should not form part of the recycled content accounting process. Carbon counting is also open to some ill-estimation due to non-carbon intermediaries, such hydrogen or nitrogen, following the same issues as simple mass allocation.

A more applicable method already used in petrochemical refineries is that of the LHV, the EMF concluded this would be "the pragmatically preferred option." Figure 3 shows an accounting example for polyamide production from mixed polyester waste from the EMF highlighting issues with other methods. Comments on mass balance stated there is potential applicability of current mass balance approaches (woodfuel, palm oil) to CR, and that it is unnecessary to fully "reinvent the wheel".

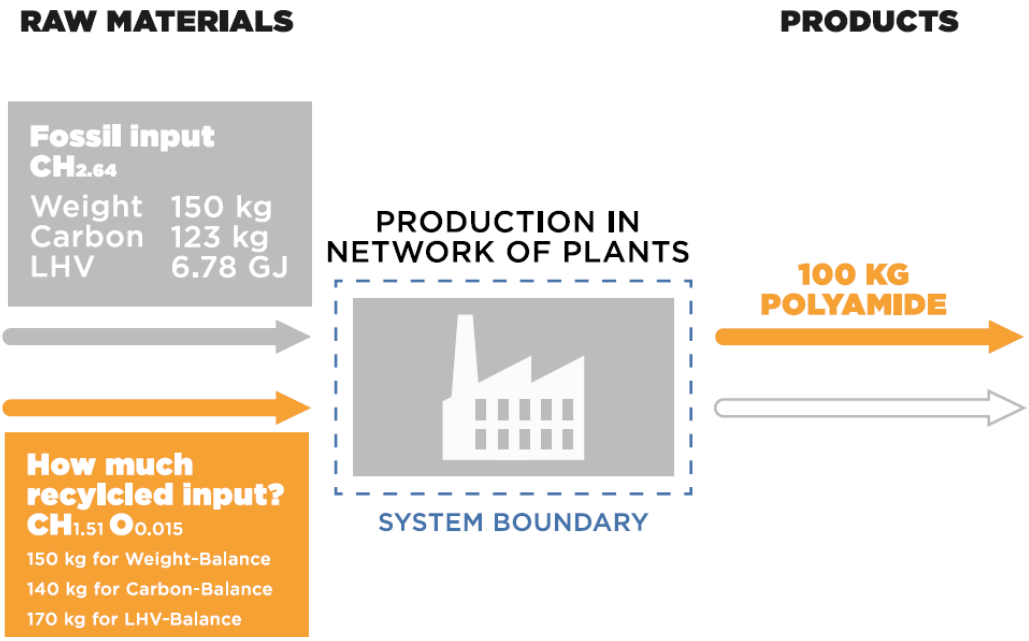


Figure 3: Example allocation procedure for polyamide production from mixed polyester waste; showing the mass of recycled input required to replace 150 kg of fossil raw materials. I.e. 140 kg of recycled feed would be required to replace 150 kg of fossil raw material following a carbon counting method. Reproduced from the EMF: Enabling A Circular Economy For Chemicals With The Mass Balance Approach

[49] *Enabling a circular economy for chemicals with the mass balance approach - the Ellen MacArthur Foundation*

[50] *Recycled content used in plastic packaging applications - BPF, CTPA, FDF*

Along with the EMF, The International Sustainability & Carbon Certification[51] (with the ISCC PLUS certification system) supports CR towards the New Plastics Economy[52]. The International Organization for Standardization (ISO) started work in mid-2020 to create a global mass balance standard for the industry[53]. Independent review by 3rd parties using a credit or certification trading model, with a definitive chain of custody to minimise (ideally eliminate) the ability for system abuse, has been put forward as a viable method. The EMF White Paper provides greater detail[54]. However, the group working on the ISO standard have opposed a credit system, stating:

"*the transfer of credits between geographies, or products, as they say that allowing this within the new global standard would not only harm the credibility of the whole industry, leading to greenwashing accusations, it would also obstruct the real change and development of the raw materials and production processes needed.*"

Instead, they recommend a Traceable Mass Balance approach – which had further support from Zero Waste Europe, ECOS, and Rethink Plastic[55]; as well as the BPF and RECOUP in a 2021 report on recycled content verification systems. From January 1st of 2022 the European Commission stated it will "adopt implementing acts laying down the rules for the calculation and verification of the targets" referring to recycled content of PET bottles[56], this was agreed upon and written into UK law at the time of adoption[57].

During consultations[58,59] on the Plastic Packaging Tax more than three-quarters of respondents agreed that the mass balance approach would be the most appropriate method though required stringent regulatory controls. Ideally a system would be globally recognised and have additional standardised provisioning to ensure operation is environmentally and socially responsible. To date there has been a lack of movement towards acceptance of such a procedure by UK regulators who may fear system abuse. However, stakeholder interviews highlighted that the UK government has already accepted the use of mass balance approaches for palm oil[60] and woodfuel[61]. Acceptance of mass balance would improve the economic viability of chemical recycling. Price competition with virgin material remains but the Plastic Packaging Tax would provide an incentive for producers to procure CR material and thereby support industry growth.

---

[51] *The Mass Balance Approach: The ISCC System - iscc-system.org*

[52] *The New Plastics Economy - the Ellen MacArthur Foundation*

[53] *Press Release: ISO development of global mass balance standard*

[54] *Mass Balance White Paper - the Ellen MacArthur Foundation*

[55] *Determining recycled content with the 'mass balance' approach -Zero Waste Europe*

[56] *Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment Article 6(5)*

[57] *Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment - legislation.gov.uk*;

Letter from The Rt Hon Thérèse Coffey MP to The Rt Hon. Lord Boswell on Directive 2019/904 - parliament.uk

[58] *Plastic Packaging Tax - Consultation - gov.uk*

[59] *Plastic packaging tax: summary of responses to the policy design consultation - gov.uk*

[60] *UK statement on sustainable palm oil: final progress report - gov.uk*;

UK consumption of sustainable palm oil: annual review - gov.uk

[61] *Woodfuel Mass Balance and Consignment - gov.uk*

2.2.1 Digital Technologies: Blockchain

Blockchain is a Distributed Ledger Technology (DLT)[62]. DLTs are a decentralised database used to keep records of digital events (such as transactions) shared by a user network, but without centralised management. Records of information (quantity, time-series, chemicals) are stored permanently and immutably in 'blocks' that, once validated in the network, are closed – ensuring the record permanence[63]. The information is viewable by anyone, vastly increasing transparency of the chain. Blockchain is most widely known for use with cryptocurrencies, such as Bitcoin or Ethereum. Such technology may offer a solution to monitoring substances of concern in a chemical recycling mass balance system following the traceability and chain of custody (molecular stewardship) issues discussed in the previous section. Blockchain could enable and ensure proper management and processing of many waste substances (not just those under CR) and provide the means to mass balance implementation.

However, there are many implementation and maintenance barriers to overcome before full system benefits can be garnered that stretch across intra- and inter-organisational, system, and legal/external factors. Establishing a shared information system, whether blockchain or other, requires possible expensive large-scale cross-chain collaborative digital transformation (hardware, software, training) that all actors must have access to and knowledge of. Within this the issue of privacy and intellectual property is unresolved, exactly what information will be logged and who will it be shared with? This could be somewhat overcome in a private blockchain though this limits data transparency, the decentralisation advantage, and may require verified keys to assure actor legitimacy. Transactions are created without any approval or verification, while other DLT nodes in the system can 'reject' anything incorrect, if one does get recorded it will be a permanent 'scar' in the records. Furthermore, responsibilities in a blockchain are not shaped solely by transactions, EPR may therefore generate uncertainty in the system.

Blockchain requires many issues to be resolved before implementation into the CR value chain could begin though the same is true of other digital systems that may not offer blockchain-specific benefits. Regardless, such systems offer potential and a new form of traceability that could have benefits reaching far beyond just chemical recycling.

2.3 End of Waste and REACH

End of Waste (EoW) is the specific criteria used to ascertain when waste ceases to be waste and becomes a product or secondary raw material (or by-product). The legislation is detailed in the rWFD and was transposed to the UK after Brexit[64]. Chapter 1, Articles 5-6 (specifically 6)[65] detail the requirements for meeting EoW status and has been adopted by all devolved nations – the specific text can be found in the box below.

---

[62] *ISO 22739:2020 Blockchain and distributed ledger technologies — Vocabulary*

[63] *Saberi, S.; Kouhizadeh, M.; Sarkis, J.; Shen, L. Blockchain Technology and Its Relationships to Sustainable Supply Chain Management. Int. J. Prod. Res. 2019, 57 (7), 2117–2135. https://doi.org/10.1080/00207543.2018.1533261*

Taylor, P.; Steenmans, K.; Steenmans, I. Blockchain Technology for Sustainable Waste Management. Front. Polit. Sci. 2020, 2 (December), 1–5. https://doi.org/10.3389/fpos.2020.590923

[64] *Definition of waste: 2018 Waste Framework Directive amendments - gov.uk*

[65] *Directive 2008/98/EC on waste and repealing certain Directives: Chapter 1 Articles 5-6*

Revised Waste Framework Directive, Chapter 1, Articles 5(1) and 6(1-2): by-products and end of waste status

Article 5 By-products (1):

1. Member States shall take appropriate measures to ensure that a substance or object resulting from a production process the primary aim of which is not the production of that substance or object is considered not to be waste, but to be a by-product if the following conditions are met:
   a. further use of the substance or object is certain;
   b. the substance or object can be used directly without any further processing other than normal industrial practice;
   c. the substance or object is produced as an integral part of a production process; and
   b. further use is lawful, i.e. the substance or object fulfils all relevant product, environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts.

Article 6 End-of-waste status (1):

1. Member States shall take appropriate measures to ensure that waste which has undergone a recycling or other recovery operation is considered to have ceased to be waste if it complies with the following conditions:
   a. the substance or object is to be used for specific purposes;
   b. a market or demand exists for such a substance or object;
   c. the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and
   d. the use of the substance or object will not lead to overall adverse environmental or human health impacts.

2. The Commission shall monitor the development of national end-of-waste criteria in Member States, and assess the need to develop Union-wide criteria on this basis. To that end, and where appropriate, the Commission shall adopt implementing acts in order to establish detailed criteria on the uniform application of the conditions laid down in paragraph 1 to certain types of waste.

Those detailed criteria shall ensure a high level of protection of the environment and human health and facilitate the prudent and rational utilisation of natural resources. They shall include:

   a. permissible waste input material for the recovery operation;
   b. allowed treatment processes and techniques;
   c. quality criteria for end-of-waste materials resulting from the recovery operation in line with the applicable product standards, including limit values for pollutants where necessary;
   d. requirements for management systems to demonstrate compliance with the end-of-waste criteria, including for quality control and self-monitoring, and accreditation, where appropriate; and
   c. a requirement for a statement of conformity.

Those implementing acts shall be adopted in accordance with the examination procedure referred to in Article 39(2).

When adopting those implementing acts, the Commission shall take account of the relevant criteria established by Member States in accordance with paragraph 3 and shall take as a starting point the most stringent and environmentally protective of those criteria.

Guidance for England and Wales to meet EoW criteria[66] refers to an 11-point list of considerations for this determination[67]; similar guidance is available for Scotland[68] and Northern Ireland[69] based on the rWFD, with further guidance on importing and exporting (of waste) for all devolved nations[70].

- burden
- certainty of use
- fit for purpose
- a specific purpose
- management
- environmental harm
- common classification as waste
- disposal or recovery
- fuel or waste
- an item returned for a refund
- reuse

There is criticism of this system and list for not enabling or aiding the circularisation of wastes that do not already have a market/specific use or waste quality protocol to aid in compliance[71]. Waste Quality Protocols (WQPs) set out requirements for when certain wastes become non-waste, these can be used on a voluntary basis by industry. There are 13 WQPs[72] though no guarantee of these being in date or applicable to CR. For example, processed fuel oil[73] was reviewed in January 2021 if derived from waste lubricating oils, though support withdrawal is due 1 April, 2022[74]. Furthermore, consideration of by-products is complicated as case law is often relied upon. Scottish waste guidance[75] states: "Case law relating to 'by-products' is complex and legal or policy advice should always be sought on this issue." Stakeholders expressed that governments do not fully appreciate the time and monetary costs of the current end-of-waste process, relying too heavily on case law and the 'off-handing' of legal clarity and responsibilities.

The context above on waste status was identified as a key area of confusion for classification of substances entering, leaving, or being transported to or from chemical recycling facilities (including that for energy) within or out of the UK or EU[76]; the incineration classification from section 2.1.2 adds further uncertainty. However, using an example pertaining to anaerobic

---

[66] *Decide if a material is waste or not: general guide (updated version of part 2 of original full document) - gov.uk*

[67] *Check if your material is waste - gov.uk*

[68] *Guidance | Scottish Environment Protection Agency (SEPA) - sepa.org.uk*

[69] *End of waste regulations | Department of Agriculture, Environment and Rural Affairs - daera-ni.gov.uk*

[70] *Waste: import and export - gov.uk*

[71] *Johansson, N.; Forsgren, C. Is This the End of End-of-Waste? Uncovering the Space between Waste and Products. Resour. Conserv. Recycl. 2020, 155 (January), 104656. https://doi.org/10.1016/j.resconrec.2019.104656*

[72] *Non-packaging plastics; recycled gypsum from waste plasterboard; biodiesel; aggregate from waste steel slag; flat class; tyre-derived rubber materials; anaerobic digestate; processed fuel oil; biomethane from waste; aggregates from inert waste; poultry litter ask; compost; pulverised fuel ash and furnace bottom ash.*

[73] *Processed Fuel Oil (PFO) End of waste criteria for the production and use of processed fuel oil from waste lubricating oils - gov.uk*

[74] *Waste quality protocols review - gov.uk*

[75] *Guidance for SEPA staff. Is it waste? Understanding the definition of waste - sepa.org.uk*

[76] *Alaranta, J; Topi, T. How to Reach a Safe Circular Economy? - Perspectives on Reconciling the Waste, Product and Chemicals Regulation. J. Environmental Law. 2020, 33 (1).* https://doi.org/10.1093/jel/eqaa016

digestion (AD), Defra[77] stated that, as already highlighted in section 1.1, deviation from the Waste Hierarchy is possible. The box below demonstrates the commentary on how AD can count towards recycling targets and meet EoW. Pyrolysis and gasification are referenced in further guidance[78] for EfW from AD, but only to produce energy or fuels. Given that these technologies are common in chemical recycling operations there is potential to align with currently accepted methods of waste disposal, EoW, and recycling targets within the WFD.

Anaerobic Digestion Strategy and Action Plan – Defra (2011)
"In most cases, the **principal purpose of consigning waste to AD is to recover energy** from it. This means that in most cases the anaerobic digestion of waste will be classified as 'other recovery' for the purposes of the waste hierarchy." "Under certain circumstances waste from households used in **AD can count towards recycling targets** set in the rWFD." "The target set by Article 11(2)(a) of the rWFD16 to recycle 50% of waste from households by 2020. As to what counts towards this target, the two main factors are the definition of 'recycling' in Article 3(17) of the rWFD and the target compliance rules to be adopted under Article 11(3) of the rWFD. The target compliance rules have not yet been adopted. However, the indications are that **the input to AD of biodegradable waste from households may be counted as recycled for the purposes of demonstrating compliance** with the target where the treatment results in digestate which **meets end-of-waste status**. Pending the adoption of EU-level end-of-waste criteria for digestate under Articles 6(1) and (2) of the rWFD, this would mean compliance with the national 'End-of-waste criteria for the production and use of quality outputs from AD of source-segregated biodegradable waste'."

Once EoW has been achieved substances are controlled under REACH. REACH here refers to UK REACH, replicated from EU REACH with alterations for operation in domestic context. It is now the duty of companies to ensure compliance and substance registry across both legislation if operating across Great Britain and the EU/EEA/Northern Ireland[79]. REACH does not apply to substances deemed waste (Article 2(2))[80]; however, there is overlap with EoW highlighted by stakeholders as another element of confusion – as REACH can provide hazard information for waste[81]. Without clarification on the former there were concerns of non-compliance; it is therefore unclear how any produced substances (including gases) should be classified. As plastics (or other polymers/chemicals) being circularised via CR may contain or be classified as harmful substances it is paramount that EoW and REACH are clarified to meet the requirements of UK REACH and the rWFD requirements; moreover, that there is agreement across borders following changes to the Prior Informed Consent regulatory regime[82] for transportation of substances.

[77] *Anaerobic Digestion Strategy and Action Plan - gov.uk*

[78] *Generating energy from waste, including anaerobic digestion - gov.uk*

[79] *UK REACH: What is UK REACH? - hse.gov.uk*

[80] *Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Chapter 1 Article 2(2)*

[81] *REACH Substances Recovered from Waste | Health and Safety Executive Northern Ireland - hseni.gov.uk*

[82] *Export and import of hazardous chemicals (PIC) from the 1 January 2021 - HSE*

2.4 Incoming Policy

The UK government has announced numerous incoming policies that will affect recycling sector operations. These included the Plastic Packaging Tax, Deposit Return Scheme (DRS), Extended Producer Responsibility (EPR), and Consistent Collection for households and businesses. An indicative timeline is below.
The Plastic Packaging Tax[83] (beginning April 2022) is a new tax that applying to plastic packaging produced in, or imported to, the UK that does not contain 30% recycled content by mass. It will not apply to any plastic packaging which contains at least 30% recycled plastic, or any packaging which is not predominantly plastic by weight.

DRS Consultations[84] were held in 2021 for England, Wales, and Northern Ireland with a government response due early 2022[85] and implementation expected in 2023[86]; the Scottish DRS will be operational from 1st July 2022[87]. The current DRS scope from consultations includes polyethylene terephthalate (PET) and high-density polyethylene (HDPE) plastic bottles, steel and aluminium cans, and glass bottles though this may be subject to changes.

Consistent Collection consultations were held in 2019[88] and 2021[89] for England and will follow a phased implementation expected to begin October 2023; similar approaches will be standardised for Scotland, Wales, and Northern Ireland. This measure will introduce a harmonised system where local authorities collect the same materials having a standardised labelling system.

Extended Producer Responsibility[90] (EPR) is a reform with initial intended (phased) implementation from 2023 that will see producers pay the full costs of dealing with the packaging waste they produce. However, in early March 2022 Defra announced a delay to this implementation date, with a new timeline now published[91]. EPR will be implemented (phased manner) from 2024. Compostable and biodegradable packaging will be labelled as "do not recycle" until infrastructure is in place and evidence that there are "ecological or agricultural benefits to soils or digestate when properly broken down." The Packaging Recovery Notes (PRNs) and Packaging Export Recovery Notes (PERNs) system will continue to be used. When EPR is at full operation (see indicative timeline below) these are likely to be phased out, though this timeline is also unknown. Once the scheme administrator is mobilised the process of establishing how fees from producers can be raised will begin. This will go towards covering the full net costs of managing household packaging waste for Local Authorities (LAs).

---

[83] *Plastic packaging tax - gov.uk*

[84] *Introducing a Deposit Return Scheme in England, Wales and Northern Ireland - Defra*

[85] *Introduction of a deposit return scheme in England, Wales and Northern Ireland - gov.uk*

[86] *Introducing a Deposit Return Scheme (DRS) in England, Wales and Northern Ireland - gov.uk*

[87] *Deposit Return Scheme - zerowastescotland.org.uk*

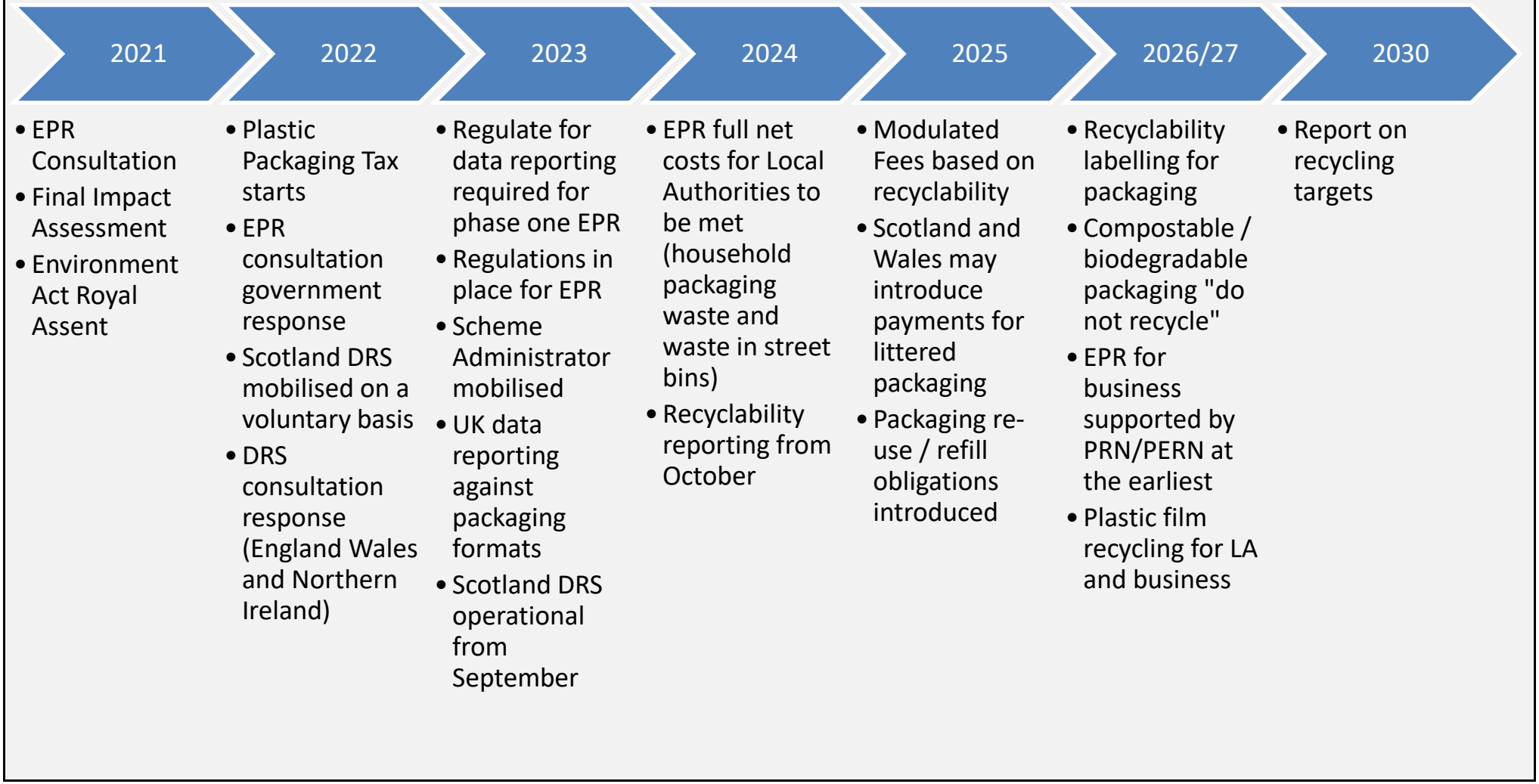
[88] *Consultation on consistency in household and business recycling collections in England (2019) - gov.uk*

[89] *Consultation on Consistency in Household and Business Recycling in England (2021) - gov.uk*

[90] *Extended Producer Responsibility for Packaging. Consultation Document March 2021 - gov.uk*

[91] *Extended Producer Responsibility for Packaging. Summary of consultation responses and government response March 2022 - gov.uk*

Indicative timeline for incoming policy



There is a lack of clarity in how payments will be distributed to waste reprocessors. The guidance documentation makes clear reference to funding local authorities and modulated fees, but little information is available otherwise (see box below). This has caused concern in the waste management sector as the uncertainty is hindering timely investment to meet the requirements of other incoming policy, such as Plastic Packaging Tax and Consistent Collection.

EPR for Packaging Consultation (March 2021) – allocation of payments uncertainty
"enabling initial payments for household packaging waste to local authorities from October 2023" "the costs paid by producers fund local authorities for the collection and management of household packaging waste and fund the collection for recycling of household-like packaging waste" "payments to local authorities and other service providers are fair and transparent and they understand any conditions that apply"
EPR for Packaging Consultation (March 2022)
"We will continue to explore payments for commercially collected packaging waste (from businesses and other organisations that pay for the collection of their waste), establishing a task force, with cross-sector representation, to develop the evidence, undertake analysis and identify options"

3.0 Perception

Many of the aforementioned challenges ultimately feed understanding and perception at governmental (between departments), public, and industry level. As the chemical recycling industry is still relatively immature there is limited information available and it is often complicated, requiring sufficient technical background to interpret. If the recycling industry is to mature with minimal public pressure a greatly improved image and understanding is required. However, industry maturation and public understanding are not mutually linked nor guaranteed. Mechanical recycling is more mature, but stakeholders emphasised knowledge and understanding are still a persistent problem especially when coupled with anti-plastic rhetoric.

A large part of the negative public perception can be attributed to a limited understanding of waste management in general and Not In My Back Yard (more commonly NIMBY[92]), with exposé pieces further damaging industry credibility. Government regulations specifically targeting plastics was also highlighted by stakeholders as impeding industry growth towards circularity as it targets the material as a lone problem, rather than more general policy based on principles of environmental stewardship in a CE for all materials. Generally speaking, the public has a growing distrust of current waste treatment systems with only 10% of people trusting the government in their role to recycle properly[93]. Greater transparency and audit trails of waste movements (see section 2.2.1) along with trusted (certified) recycled content *could* alleviate many ill-feelings of chemical recycling. However, in the absence of definitive governmental support towards such measures, reports of UK illegal UK waste exports, and the continued (general) lack of waste treatment understanding this position may not change positively in the short term.

Chemical recycling has closer affiliation to 'Big Oil' than MR and this was seen as a large image barrier with climate change at the forefront of media and policy objectives. Some stakeholders

[92] ***N**ot **I**n **M**y **B**ack **Y**ard - a stance taken in which individuals or groups object to the placement of something perceived as unpleasant or hazardous in the area where they live, especially when raising no such objections to similar developments elsewhere.*

[93] *Viridor UK Recycling Index 2019*

stated that chemical recycling was a 'change enabler' for petrochemical companies to circularise their material flows, as the modern world will continue to require derived products so too will it require new technologies to treat inevitable wastes. Further, reports from some non-governmental organisations increase awareness of chemical recycling but in a negative light. For example, a recent (USA-centric) report from Greenpeace[94] stated that chemical recycling is an "intentionally vague term" and a "false solution", recommending that Fast-Moving Consumer Goods companies should not consider, "invest in, agree to offtake plastic from, or join development consortium". The same report commented on the number of promises not being met as a failure of the industry overall; this was cited by stakeholders as an additional challenge for a young disruptive industry as some failures were economically (financially) or legislatively driven, rather than technically, and that many companies would inevitably initially fail as supporting sectors adjusted. Stakeholders were keen to see more long-term industry goals rather than promises.

4.0 UK Infrastructure and Investment

According to a 2016 McKinsey report[95] just 12% of the 260 million tonnes (Mt) of global plastic waste was recycled in 2016, this is expected to double to 460 Mt by 2030. They estimate in a high-adoption recycling case that, to meet a 50% recycling rate, between $15 billion and $20 billion (~£11.4bn to £15.2bn as of Dec 2021) will need to be invested per year in infrastructure (average petrochemical/plastics industry yearly investment over the past decade have been between $80 billion and $100 billion (~£60.6bn to £75.8bn as of Dec 2021)), with estimated 20-year investments being ~€2.7 trillion[96] (£2.3tn as of Dec 2021).

The economics of CR differ somewhat to that of MR and other methods, as they can potentially provide virgin quality materials while meeting recycled content thresholds, though ultimately product demand remains in competition with volatile oil price fluctuations from a financial perspective. McKinsey analysis suggested that waste plastic conversion to naphtha could still remain profitable (via pyrolysis) down to $50 a barrel; however, this will likely need revision due to geopolitical struggles and changing markets. Projections to 2050 indicate a fall in demand for oil, with petrochemicals and plastics expected to make up some of this loss. If circularisation (via CR and other means) continues to increase up to 2050 a new relationship between stakeholders in the oil, plastics, and chemicals value chain will form. As much of the CR feedstock is tied to currently uncaptured (at kerbside) fast-moving consumer goods packaging, and involves many stakeholders, there is little certainty on what form this will take, due to its unprecedented nature in linear industrial economies. Scaling small circular economy business models from a disruptive industry into a transitioning linear system requires an improvement in networking ability (and overall sector growth) to reap full advantages. Market signals for recycled content in plastic are emerging globally but supporting regulation is slow to update and be inclusive of new technologies. For example, there is scant mention of chemical recycling in any UK or EU environmental or waste management target documentation. At this point it should be evident that all points create significant hesitancy for investors in this field, making SME growth difficult towards establishing the sector. Thus, SME support is required on this front.

As CR interfaces between waste management and chemical processes, exploiting pre-existing petrochemical infrastructure investments is an option to curtail prohibitive start-up costs and unnecessary segregation of recycled material flows into separate plants. This would enable potential use of current transport infrastructure at large scale industrial parks if plants are co-

[94] *Deception by the Numbers - Greenpeace*

[95] *Recycling and the future of the plastics industry - McKinsey & Company*

[96] *Mass Balance White Paper - the Ellen MacArthur Foundation*

located. For such advantages to be captured the locality and scale (and scalability) are key factors – especially for access to adequate feedstocks. Moreover, that collaboration across the entire value-chain from those placing on market to those 'taking off market' before return was required. Stakeholders stated some hesitancy from cracker operators in using CR substances due to heterogeneity and impact on normal process operations depending on the feedstock composition, partially confounded as a result of new materials and designs[97]. However, facilitating improved engagement between CR and petrochemical companies towards specifications[98] can alleviate some concerns while also assisting in meeting EoW test requirements by facilitating certainty of use.

There are currently no commercially operating CR facilities in the UK[99] though a number are planned, typically as modular co-locations but not in all cases. The viability of ventures is partially dependent on funding allocation, acceptance of mass balance to incentivise CR demand (section 2.2), and integration of CR into the UK's waste management plan. Incoming EPR and the Plastic Packaging Tax are intended to provide funds towards UK growth, however, as the payment process is unclear, multiple policy are concurrently phased, and reports on recycling targets are not expected till 2030 it is unclear how sufficient finance can be secured during this period. Nevertheless, CR infrastructure (pilot and commercial scale) are developing in the UK, for example (non-exhaustive, in no particular order):

- ReNew ELP are currently constructing a 20 ktpa (kilo tonne per annum) plant in Teesside, North England, which will reach 80 ktpa capacity once completed.
- Quantafuel are planning to expand their operations in Sunderland.
- Enval are expanding their process, capable of recycling aluminium laminates, in Mexico and have a pilot plant set-up in the UK.
- Project Beacon (including companies Polymer Recycling, Recycling Technologies, and Impact Recycling) will be a co-location build at Binn Eco Park, Perthshire, Scotland. The build will include multiple mechanical and non-mechanical technologies to facilitate the circularisation of plastics.
- Orthios and Totus are planning to construct a site capable of handling 50 ktpa of films and flexibles in Anglesey, Wales.

RECOUP[100] concluded that current UK household plastic packaging sorting capacity at both MRFs and PRFs (Material- and Plastics-Recycling Facilities, respectively) is not a barrier to meeting the 30% requirement of the Plastic Packaging Tax. They estimated total MRF sorting capacity to be between 1.6 and 1.9 Mt, with estimated actual throughput of 0.8 to 1.0 Mt (from 110 MRFs and 7 PRFs capable of sorting household plastic packaging). However, there are "significant shortfalls" in reprocessing capacity with only 16 reprocessors capable of manufacturing washed flake from household plastic packaging. They estimate reprocessing capacity at 440 kt with an estimated actual operational output of 230 kt. Four scenarios for meeting the 30% recycled content were put forward, the smallest reprocessing shortfall (assuming target met for only rigid household plastic packaging) was 110 kt, representing almost 50% of current actual UK capacity. Figures from the UK Plastic Pact working group towards Target 4 (30% average recycled content across all plastic packaging by 2025) estimate the figure to be larger, with 10 new facilities (estimated capacity >225 ktpa) required. Regardless of capacity tonnage estimations there is agreement

[97] *Frączak, D.; Fabiś, G.; Orlińska, B. Influence of the Feedstock on the Process Parameters, Product Composition and Pilot-Scale Cracking of Plastics.* Materials ***2021***, 14, *3094.* https://doi.org/10.3390/ma14113094

[98] *Burgess, M.; Holmes, H.; Sharmina, M.; Shaver, M. P.; The future of UK plastics recycling: One Bin to Rule Them All.* Resources, Conservation and Recycling *2021,* 163, *105191.* https://doi.org/10.1016/j.resconrec.2020.105191

[99] *Note there are a number of UK pilot plants already operating.*

[100] UK Household Plastic Packaging and Reprocessing Infrastructure Report 2020 - RECOUP

that the rate of increase in demand for recycled content in the UK will surpass the rate at which new infrastructure can be constructed – leading to a reliance on imports. This statement does not factor in changes to collections or material composition nor the volume of currently imported plastic packaging material. The import market may therefore become a primary source for plastic packaging meeting the 30% content target, strengthening foreign producers and creating additional struggles for domestic competition.

In total approximately 2,290 kt of plastic packaging was placed on market, in 2019, according to Valpak[101]; of this, 311 kt is consumer film and 354 kt is non-consumer film (total 665 kt). Chemical recycling is expected to handle the more 'difficult to recycle' polymers on the market, such as films and flexibles (LDPE and PP). Only 14% of local authorities (~30) currently collect film, estimated to be around 22 kt or 7% (RECOUP, 2020) of that put-on market. There are now more than 3,500 front of store collection points for flexible plastics but this is expected to reach 6,000 by January 2022[102]. Consistent collection (expected October 2023) of films for household at kerbside is not expected to begin until 2026/27 (England) as part of phased implementation. It is unclear how long front of store will operate once kerbside collection begins. The coincidence of low kerbside collection rates, expansion of front of store points, and imminent plastic packaging tax leaves a considerable time frame in which there is confusion on how enough material will be captured and converted into recyclate, especially for applications such as food or medical contact. In addition, transportation of flexible plastic waste (often at higher cost due to low density before baling) with multiple collection systems in place and uncertain ends, add uncertainty to the end recycling destination – if at all. As there are no standards for MRF bale quality, only guidance such as that from Zero Waste Scotland[103] or The Association of Plastics Recyclers[104], further concerns arise with respect to feedstock quality even after Consistent Collections are phased in across the UK.

[101] *PackFlow COVID Report - Valpak*

[102] *The UK Plastics Pact Annual Report 2020/21 - WRAP*

[103] *Guidance on sorting and processing of plastic bales for MRFs - Zero Waste Scotland*

[104] *Model Bale Specifications - The Association of Plastics Recyclers*

5.0 Conclusions

The UK waste management sector is already mature, having a complicated series of systems and legislation to enable the collection and sorting of material. Resultingly, the implementation of new non-mechanical recycling processes into these systems is a significant challenge. These challenges are substantially underpinned by legislative uncertainty with a plethora of phased reforms incoming over the next decade.

Reforms are being implemented as all UK nation governments have made commitments to improve the circularity of waste and resources. After the preferential reduce and reuse, recycling is the final instrument at play. However, present systems and technologies are not capable of meeting these alone, even with improvements. It is therefore imperative that technical innovations are supported with investments and integrated to create a more robust sector. If support is not given the UK chemical recycling industry, including retailers and others who could utilise produced materials for recycling targets, may falter on commitments or incoming policy requiring action. Consequently, emerging non-mechanical (chemical) businesses face an 'uphill struggle' for adoption.

Chemical recycling requires recognition as part of a solution to circularisation, particularly for plastics. Therefore, creating harmony across standards and legislation considering the international implications should be a priority. Discussion on this includes definitions, acceptance of material for meeting recycled content targets, clarity on new legislation and applicability to non-mechanical recycling (including funding allocation from new reforms to assist investment), improvements in (waste) feedstock quality after collection and sorting, and meeting End of Waste and REACH to promote the best environmental outcome and ease movement of what are not resources, rather than waste. These areas should also be considered towards the (long-term) financial viability of chemical recycling and its ability to compete in mature markets. A highly important but broad theme across these areas is the necessity for collaboration, for those involved in the discussions, to be improved and facilitated impartially. The consistent highlighting of the lack of understanding by disparate but dependent stakeholders alludes to this necessity.

These factors are not exhaustive, all are systemically entwined and mapping these challenges is extremely difficult. It is paramount that challenges are considered together if non-mechanical recycling is to form as an integral part of the UKs future waste management operations.