Journal of Polymers and the Environment
https://doi.org/10.1007/s10924-023-02792-3

ORIGINAL PAPER

Hydrothermal Treatment of Waste Plastics: An Environmental Impact Study

Matthew C. Ozoemena[1] · **Stuart R. Coles**[1]

Accepted: 7 February 2023

Abstract

This paper presents the attributional life cycle assessment results of a study of plastic recycling *using* hydrothermal treatment (HTT), a chemical recycling technology. HTT was investigated due to its potential to address current gaps in the plastic recycling system, largely due to several plastic packaging materials and formats that are currently not processed by traditional mechanical recycling technologies. As society transitions towards a net-zero-based circular economy, assessments should be conducted with a futuristic outlook, preventing costly mistakes by employing the right technologies in the right areas. The results using ReCiPe 2016 impact assessment methodology shows HTT with a GWP of 478 kg CO_2 eq. per tonne can generate up to 80% reduction in climate change impacts when compared with comparable end-of-life treatment technologies whilst conserving material with the system. Additionally, the GWP could be reduced by up to 57% by changing how electricity is generated for on-site consumption. This represents a new understanding of the chemical recycling of polymers by establishing a prospective life cycle assessment study that looks to introduce a step-change in the recycling system and highlights the benefits of introducing this technology as opposed to the current model of disposal through incineration or landfill.

Keywords Hydrothermal treatment · Naphtha · Life cycle assessment · Chemical recycling · Waste plastic

Introduction

The phenomenal growth of the plastics industry has resulted in a vast number of plastics produced worldwide every year, contributing to the materialistic affluence in human living [1, 2]. However, the abundance of plastic goods in the world has also created serious environmental problems [2]. Globally, around 367 million tonnes of plastic waste is produced annually and with predicted plastics demand, the global annual production of waste plastic will almost double by 2030 [3]. The ever-increasing amount of plastic waste is overwhelming conventional waste management infrastructure – landfill, waste to energy technologies, mechanical recycling - globally [3]. In the UK and the EU, disposal of waste to landfill has been significantly reduced through environmental regulation, driven by market measures and so protect the environment from intractable impacts including hazardous leachate, groundwater pollution and gaseous emissions [4]. New obligations for separate collection of waste such as bio-waste and textiles were introduced and an overall 70% recycling rate target to be met by 2030 for all packaging materials was set [5]. A recycling target per material type was implemented and targets to limit landfilling rates to 10% by 2035 were introduced [5].

Following governmental direction in the UK [6, 7] EU[5] and developing countries where plastic is a symptom of economic growth,[8] solutions are being sought to address the recycling of currently non-recyclable, single use plastics, but to do so in a way that makes both environmental and economic sense. Within the UK and the EU, the recycling of post-consumer plastics at scale, following mixed waste collection from the domestic and commercial settings, is a very complex challenge [9, 10]. Plastic bottles (PET & HDPE) are extracted and sent to recyclers for closed loop recycling, whereas other plastics, roughly sorted into single polymer bales, are sent for further processing to Material Recovery Facilities (MRFs) or exported for incineration [10]. Polymers which can be sorted to a high degree of purity at MRFs

---

✉ Stuart R. Coles
stuart.coles@warwick.ac.uk

[1] WMG, University of Warwick, 6 Lord Bhattacharyya Way, Coventry CV4 7AL, UK

are mechanically recycled using heat and pressure treatments to form flakes or pellets which can be extruded or blow moulded into new uses [11].

Using mechanically recycled plastic in higher-value applications is technically challenging and leads to increased process rejects and a generally lower quality of product, which is why traditional mechanical recycling processes are often referred to as 'down-cycling' [12]. It is possible to generate good quality products via mechanical recycling provided there is good control of the quality of the input feedstock [9]. Optimally, mechanical recycling requires clean, homogeneous feedstocks, which will require sorting, and cleaning to remove grit and food residues, and contamination (paper, card, and other non-target materials) [10]. But such processes do not remove embedded colour, separate different polymers or other materials in multi-layer packaging or address deep contamination of the plastic; all of which influence the recyclate end-market and valorisation [10]. Chemical recycling processes are however able to tolerate a wider range of non-homogeneity of post-consumer plastics, relative to traditional re-processors and therefore these offer a practical solution at scale, as part of a circular economy model for plastics [9]. Chemical recycling has been defined by the industry as *"any reprocessing technology that directly affects either the formulation of the polymeric waste or the polymer itself and converts them into chemical substances and/or products whether for the original or other purposes, excluding energy recovery"*[13].

Hydrothermal treatment (HTT) combines the process characteristics of pyrolysis (high heat) and solvolysis (dissolution) to heat, melt and then dissolve in steam the mixed plastics feedstocks under supercritical conditions (> 373 °C, > 220 bar) [14]. In this process setting, polymers are broken down into short-chain hydrocarbons, with the water acting as a hydrogen ion donor to reduce excess cracking and free-radical formation [14]. The steam-hydrocarbon mix is then passed through a reactor system and depressurised to flash distil the products out across the range of boiling points [14]. The catalyst is not broken down or consumed in the reaction, nor does it need regeneration [14]. Through the direct transfer of heat to the plastic *via* the supercritical water process environment, there are no obvious limitations to process scale up. Additionally, as it is not a direct-heating combustion process, HTT does not create harmful combustion by-products such as dioxins and does not produce char as a by-product of conversion reactions, and so helps to maximise higher product yields than that of other thermal process technologies such as pyrolysis [15] and gasification [16]. The aim is that through chemical recycling, a step-change in the recycling system will be made to address 'performance gaps' left by traditional mechanical recycling technologies, that otherwise directs waste plastic to incineration or landfill. However, there has been some concern that the energy demand associated with chemical recycling, due to the process conditions involved, makes these processes more environmentally damaging [17]. Moreover, identifying a sustainable pathway to net zero requires operators to consider consumption, process efficiency and renewable energy as options to ensure that circular systems deliver better environmental outcomes than the conventional systems.

To understand the environmental impact more clearly, life cycle assessment (LCA) must be completed in a consistent manner to be able to compare the benefits and weaknesses of technologies. Previous work has looked at how chemical recycling can contribute to reducing emissions but without emphasis on a particular technology [18–20]. It was suggested plastics that are difficult to handle through mechanical recycling be chemically recycled. Thus, 11% of total end-of-life plastics could be chemically recycled in addition to the existing mechanical recycling capability. Furthermore, existing LCA studies that covered chemical recycling have been reviewed [21] but it was highlighted there were only a handful of studies in this area. Some other commissioned studies have focused on technological comparisons aiming to analyse the environmental impact of using chemical recycling technologies compared to traditional plastic waste treatments landfill and incineration [22, 23]. Pyrolysis showed better performance compared to landfill and incineration particularly in the category of resource scarcity where negative impacts were observed. Furthermore, existing studies in this area have relied on industrial scale production data for one chemical recycling technology (pyrolysis) [23] or others based on demonstration plants that are in use but not yet at commercial scale [22]. Studies assessing pyrolysis in the UK, Singapore and Europe suggest the climate change impact is significantly lower than that of incineration [24–27] The results show that chemical recycling via pyrolysis has between a 30–50% lower climate change impact. Whilst interesting, it should be noted that chemical recycling is likely best viewed as complementary to existing techniques such as mechanical recycling, rather than a competitor, due to the diverse range of feedstocks that it can process.

A study on pyrolysis to produce propylene and ethylene monomers in the United States found a significant influence on the climate change impacts due to regional grid mixes [28] The GHG emission results showed that ethylene, propylene, and aromatics mixture (1.08, 1.10, and 1.16 kg CO_2 eq. per kg, respectively) are equal to or less than those of fossil products assuming the U.S. average electricity grid. An evaluation of regional electricity grids on GHG emissions for all products was also conducted for 50 states in the U.S. Analyses was presented on waste management in countries and European cities and compared with pyrolysis of plastic waste to produce petrochemicals including gasoline, propane and butane [29–31]. The pyrolysis scenarios they examined appear to offer environmental benefits in terms of consumption of fossil fuel resources and GHG emissions in comparison to reference scenarios like material recovery, combustion, and landfilling. The scenarios result in the highest savings in terms of eutrophication potential mainly due to the avoided impact for the naphtha production. Other studies have reported pyrolysis of plastic waste as offering more environmental benefits, such as reduction of GHG emissions, when compared to other plastic waste treatment options [32–35]. The pyrolysis scenarios performed better than the incineration scenarios with respect to the impact categories of global warming potential and freshwater ecotoxicity.

As can be seen from the literature there have been several studies done on LCA of plastic waste treatment via pyrolysis, [21, 24–32, 35], but none using HTT. Consequently, the aim of this paper is to carry out the first LCA study of recycling mixed waste plastics into a naphtha-like fraction using relevant industrial data for a scaled-up facility, specifically *using* HTT, to understand its environmental impacts and where potential savings can be made for the future.

Materials and Methods

The LCA was conducted following the guidelines contained within ISO 14,040/14,044 recommendations [36, 37]. This is broken down in the following subsections.

Goal and Scope Definition

The primary goal of the study is to carry out an assessment of HTT to understand its impact on the environment. The scope is gate-to-‘end of waste’ using an attributional cut-off approach, focusing on understanding the potential environmental impact of the activities themselves. The terminology ‘end of waste’ is chosen to match with the fate of materials as determined by the Waste Framework Directive [38]. The HTT process was modelled on the HydroPRS™ technology and is located at a facility which is currently being constructed at the Wilton International Site in Teesside, UK. As such, this is a pre-operational assessment based on conservative estimates for the process, using a standardised approach of estimating the highest potential usage or consumption of the relevant inputs.

For this study, the waste feedstock materials will be assumed to have zero environmental impact (as the burden is assumed to lie with the primary production) and the focus will be on the recycling operations itself. The boundary will start at the journey of the material to the Wilton site and ends with the production of the five product streams generated by the HTT process. Electricity was sourced from a mix of 16% biomass and 84% UK grid mix, based on BEIS 2020 data [39], as is expected to be supplied to the Wilton site.

Functional Unit, Data Collection and Allocation

The functional unit for this study is the processing of one tonne of waste plastic feedstock. Primary data for the HTT process was supplied by ReNew ELP based on projections from the facility design stage. As this is a process to produce material feedstocks for the chemical industry, a mass-based allocation approach was taken with the co-products. A procedure based on allocation by economic value was considered but not progressed due to the prospective nature of the assessment and the true economic value of each of the products not being fully realised at this stage, as well as the changing economic conditions that were being experienced during the development of the work. GaBi software was used to create the LCA models and generate impact assessments using the ReCiPe 2016 methodology (hierarchical viewpoint). GaBi software was used as it contains comprehensive LCA databases with over 15,000 annually updated datasets. ReCiPe 2016 methodology is one of the most recent and updated impact assessment methods available hence its use for the purpose of this study.

Feedstock Treatment

The overall model is effectively a cradle-to-gate process, where the environmental burden is allocated from the start of the journey of the polymer feedstock to the Wilton site. This is assumed to be 160 km by a 34–40 tonne (gross weight) Euro 6 standard truck; the distance was defined based on the likely polymer feedstock supplier. The expected composition of this feedstock was determined based on discussions with ReNew ELP and their suppliers and assigned to an end-of-life pathway to assist with the LCA development. As there are no quality standards within the UK for waste plastic bales, the supplied plastic waste feedstock is expected to contain non-target contaminants which need to be removed within a purpose-built material preparation plant (MPP) before the polymeric material can be processed within the HTT system. The feedstock is shredded, and metal contaminants are removed at this first stage. A dry clean of the shredded feedstock removes further solid contaminants such as stones, glass, wood, grit etc. These contaminants are expected to be typically 23 kg (2.3%) of inert waste (which will be transported 10 km by truck to a landfill), and 8 kg (0.8%) ferrous metal & 2 kg (0.2%)

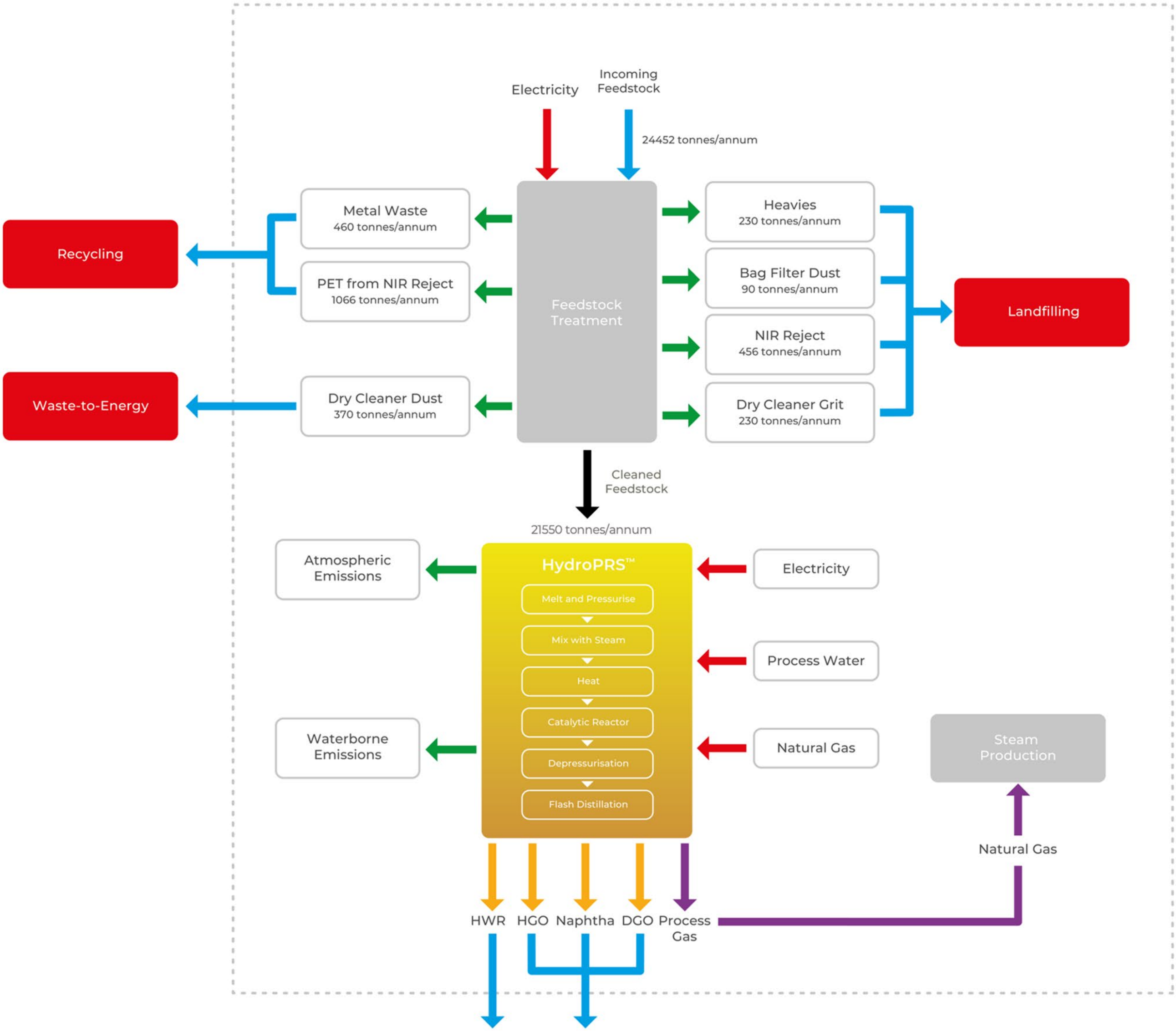

Fig. 1 Hydrothermal treatment System Boundary

non-ferrous metals (which are sold to other recyclers). The final stage of the cleaning process is a near-infrared sort to ensure only the appropriate polymers enter the process. The facility currently plans to process films and flexible plastics, largely polypropylene and polyethylene. The processing of chlorinated polymers is being avoided, so rejects include PVC as well as paper, dry cleaner dust etc. These rejects are estimated to have a total mass of 72 kg (7.2%). They are all combustible and are expected to be transported 18 km by truck to an energy-from-waste (EfW) facility. Electricity consumption for the feedstock treatment stage is estimated to be 5800 MWh/annum. Emissions from the EfW facility have not been attributed to the HTT process as that activity would have occurred regardless of a chemical recycling intervention, and thus it is not fair to attribute the activity in this instance. The remaining 895 kg of waste plastic (films and flexibles that are predominantly LDPE & PP) would be processed *using* HTT.

Hydrothermal Treatment

HTT is effectively a one-stage process (Fig. 1) with several different inputs as listed below. The year refers to the datasets used from the GaBi database. Whilst the facility is under construction and soon to be operational, some historical background datasets have been used to complete the LCA model. In all cases, it is the most recent data available. The assumption is that any changes in the datasets between 2017 and 2020 and the date of implementation are likely to be negligible. The full life cycle inventory assessment can

Table 1 Yield of potential products from HTT (as estimated by ReNew ELP)

Product	Yield Range	Yield used for LCA
Process gas	10–15%	11.4%
Naphtha	20–30%	26.0%
Distillate gas oil (DGO)	20–30%	25.3%
Heavy gas oil (HGO)	20–30%	24.3%
Heavy wax residue (HWR)	10–20%	13.0%

be found in the supplementary information. As the catalyst is not consumed within the reaction, it is not considered as an input for the process as the overall environmental impact per tonne of input is negligible.

- Electricity usage: 16 200 MWh/annum.
- Consumption of potable water (fire water, safety showers and general hygiene) – 2020 data: 900 tonnes per annum.
- Demineralised water used in the boiler – 2020 data: 14,000 tonnes per annum.
- Process water used to enhance the cooling of the system, particularly during the summer – 2020 data: 8,500 tonnes per annum.
- Process gas used onsite for steam generation: 1600 tonnes/annum.
- Wastewater treatment used to remove contaminants from the wastewater – 2020 data: 15,768 tonnes per annum.
- Natural gas consumption (start-up fuel and pilot lights) – 2017 data: 440 MWh per annum.

This inventory also includes the separation stage, whereby the mixture is depressurised, and products are separated by distillation into five product streams (Table 1). The yield of each product has an estimated range depending on the exact conditions used in the reactor, and a value within that range has been taken for the purposes of the LCA study based on an average expected value per annum.

The process differs by using steam under supercritical conditions as a solvent to break down polymeric material, with the thermal energy used to generate steam being provided by re-use of the product gas in the boiler system

The products are stored and the naphtha-equivalent fractions (naphtha & DGO, 51.3% of the total product) can be used as a steam cracker feedstock for the manufacture of polyolefins, replacing traditional petroleum naphtha, although the environmental burden of this process is not assessed as it is attributed to the downstream naphtha processing. All fractions from the HydroPRS process are registered as products under EU REACH [40] and UK REACH [41] and are therefore ‘lawful’, which is a criterion of the End of Waste under EU Waste Framework Directive [42] and UK End of Waste criteria. Therefore, any further downstream burdens will be attributable to the onward processing by the product offtakers.

Results and Discussion

Feedstock Treatment and HTT Process Stages

The complete life cycle inventory of the HTT process and overall impacts generated through the LCA process can be found in the supplementary information. The overall Global Warming Potential (GWP) of the study based on the data is 478 kg CO_2 eq. per tonne of input feedstock. The full LCA impact assessment results, calculated using the ReCiPe (H) methodology can be seen in Fig. 2, is broken down into the feedstock pre-treatment and HydroPRS™ stages. A table containing the numerical data showing the magnitude of the impacts can be found in the supplementary information.

Looking at the contribution of the two sections – the feedstock pre-treatment dominates the impact assessment in two categories, freshwater eutrophication, and natural land transformation. The natural land transformation is being driven by using landfill as a disposal method for some of the discarded materials from the pre-treatment step, and the freshwater eutrophication is also dominated by landfill as the significant contribution, presumably due to contaminant run-off from landfill sites. Alongside this, the results show that the contribution of the feedstock treatment is significant (28.6%) for the GWP of the overall process, and the contribution of the feedstock pre-treatment is between 24 and 31% in the majority of impacts, highlighting the need to investigate the feedstock pre-treatment more thoroughly as it is not negligible in the overall assessment. GWP will be the focus of this study given the global attention on dramatically reducing anthropogenic carbon emissions to limit warming to 1.5 degrees Celsius above preindustrial levels to avoid the worst impacts of climate change.

Feedstock Treatment

Looking at the GWP of the feedstock treatment in more detail (Table 2), the emissions due to electricity consumption has the largest contribution at 59% (80.2 kg CO_2eq). Waste processing activities have been assessed with the starting point feedstock treatment at the front end to protect the HTT process because feedstock is unlikely to be optimal. Carbon emissions because of the decomposition of the materials in landfill contribute 31% (42.2 kg CO_2eq). This would indicate that a simple way to improve the impacts of the pre-treatment would be to improve the bale quality received by chemical recyclers with reduced levels of contaminants, particularly those that end up in landfill; this would impact

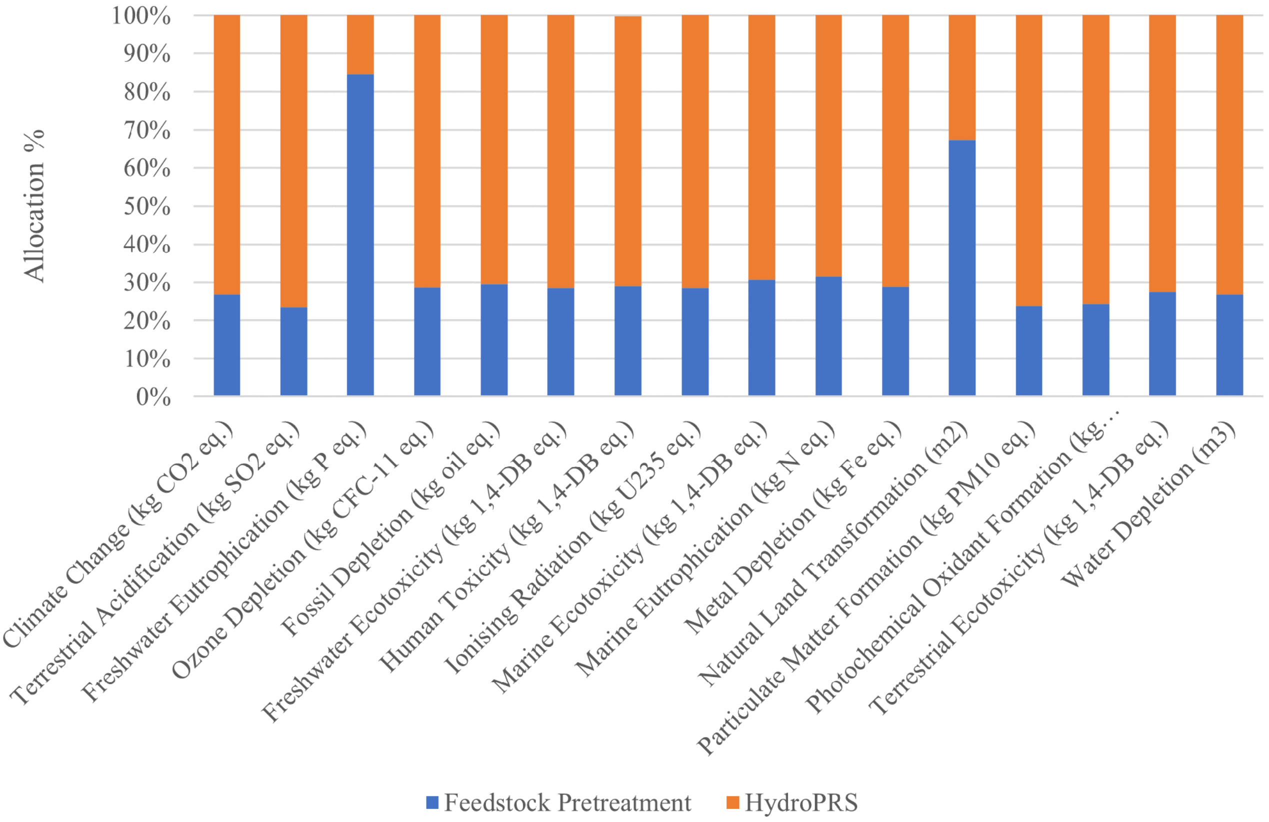

Fig. 2 Impact Assessment Results of Hydrothermal treatment

Table 2 Detail of feedstock treatment contribution to GWP

Process	GWP / kg CO_2eq	% contribution
Electricity consumption	80.2	59%
Landfill	42.2	31%
Transport & others	13.6	10%
Total	136	100%

not just the GWP but also significant contributions in natural land transformation. Additionally, as this is an attributional model, no credits for the consequences of recycling the metals sifted out at this stage have been applied, as they would be attributed to the manufacturing of any subsequent product to include recycled metal content. If a consequential approach was taken, it would only serve to improve the environmental impact, and GWP specifically, of the feedstock pre-treatment. An attributional approach gives an estimate of how much of the environmental impact belongs to the product studied[36, 37]. A consequential approach gives an estimate of how the environmental impact is affected by the product being produced and used[36, 37]. Given the scope of this study, an attributional approach is more appropriate as it does not include environmental benefits or other indirect consequences that arise outside the HTT.

Transport and other contributions are relatively small in comparison, but it is worth noting here that the contribution of transportation when allocated to a product often looks small due to the nature of the allocation process, even though transportation is a known significant contributor to GWP. Typical loadings of a 34–40 tonne Euro 6 truck would mean that around 4–5% of the emissions generated from the journey would be allocated (using an allocation by mass approach) to each tonne of plastic waste transportation, which perhaps gives the overall impression that transportation is not as significant problem as it is because it unduly masks the magnitude of the issue. These emissions could be mitigated through the use of electric vehicles[43]. Electricity consumption is the most significant contributor here, which will naturally decrease over time as the grid is made greener through planned improvements[39].

Hydrothermal Treatment

The GWP of the HTT process is estimated to be 341 kg CO_2eq. Examination of the relative contributions to GWP (Table 3) shows that the electricity consumption is the most significant contributor at 59% (201 kg CO_2eq). This is followed by process emissions at 37.2% (126 kg CO_2eq),

Table 3 Contribution of HTT process steps to GWP

Process	GWP / kg CO_2eq	% Contribution
Electricity consumption	201	58.9
Process emissions	126	36.9
Demineralised water consumption	13	3.8
Others	1	0.4
Total	341	100

mainly reflecting process gas consumption in the high-pressure boiler but also consumption on-site in a low-pressure boiler. The HTT process will reuse gas generated as a product stream so the process does not source natural gas from the grid, which is a benefit, but the gas is still being generated from what was originally a fossil-based source and the emissions should be accounted for. Other inputs into the process including water consumption and treatment are relatively minor.

Allocation and Comparison to Petrochemical Production of Naphtha

The HTT process produces five product streams, of which at least two (DGO and naphtha) can be combined and used as a replacement for fossil naphtha. This equates to 460 kg of naphtha-equivalent product being produced by 1 tonne of waste plastic processing. If the overall GWP of the process (478 kg CO_2eq) is allocated by mass to each individual product, that would mean 245 kg CO_2eq of the total GWP could be allocated to 460 kg of steam cracker feedstock production.

As a comparison, the production of 460 kg of naphtha from crude oil at a refinery within the UK has a value of 184 kg CO_2eq [44]. If the feedstock processing stage (discussed above) was removed or consolidated with other recycling activities such as mechanical recycling to produce a more optimal system, the value to produce the steam cracker feedstock could be lowered as far as 175 kg CO_2eq (utilising the same process of allocation as above). Additionally, the processes involved in the production of naphtha in a refinery are largely thermal processes that rely on energy to be produced using gas or the equivalent. There is also no accounting for flaring and other fugitive emissions in the quoted refinery model, and there is work that suggests that anthropogenic methane emissions have been underestimated [45]. This suggests that the value of 184 kg CO_2eq is likely to be an underestimate of the real figure.

Additionally, as HTT is more reliant on electrical energy, and with the grid expected to be made more carbon efficient over time, this transition will naturally reduce the GWP of HTT, to equivalent or better than fossil naphtha. It could therefore be reasonably assumed that if it is not already, in the future use of HTT to produce steam cracker feedstocks will be less environmentally damaging than extraction of virgin materials.

Table 4 Sensitivity analysis on electricity production

	Site grid mix	100% wind power	"Net zero" scenario
Climate change / kg CO_2eq	478	204	218

Table 4 shows a sensitivity analysis for the electricity supply for the HTT process, looking at if the process was powered entirely by wind energy, or a prospective 'net zero' scenario-based removing coal and gas from the current grid mix and scaling up the remaining contributions accordingly. This would be an assumed grid mix of 13% biomass, 44% nuclear, 5% hydro, 7% solar and 31% wind [44] and generates a GWP of 218 kg CO_2 eq. This is an unlikely scenario in the UK in the short-to-medium term due to the high contribution of nuclear power, but it does demonstrate the possibility of reducing the overall impact of the process significantly simply by improving the grid mix; highlighting the need for policy interventions in the energy sector to further push towards low- and zero-carbon electricity generation. The use of 100% wind power was also modelled (GWP of 204 kg CO_2 eq as there is an offshore wind farm located nearby to the site location (Teesside Wind Farm). Additionally, there is a difference between the two prospective electricity scenarios because of the varying impact of renewable energy generation technologies such as solar, biomass etc. Furthermore, the modelling of HTT is of a prospective first-generation industrial process and it is highly likely that technical improvements made for future generations of HTT will reduce the environmental burden further.

End of Life Treatment Comparisons

Whilst naphtha production is an interesting comparator, it is not the main driver for the process as HTT is a waste treatment technology and is designed to deal with end-of-life plastic materials. Plastics will continue to be produced as they have key role within society, and as such, disposal measures need to be considered and evaluated based on their environmental metrics associated with their operation.

Currently, the most common approach for disposing of hard-to-recycle films and flexibles, the target market for the HTT process, is through incineration to generate energy from waste. The disposal of one tonne of mixed plastic waste through incineration is estimated to have a GWP of 2340 kg CO_2eq [46]. This shows that HTT has approximately 80% reduction in the climate change impact when compared to incineration, when looking at the comparable disposal routes for one tonne of mixed plastic waste. This is in line with another study commissioned by the Consumer Goods Forum that has looked at the chemical recycling of

Table 5 Environmental impacts of generating 5020 MJ of electricity

	Hard coal	Hydro	Incineration (plastic)	Natural gas	Nuclear	Solar	Wind
Global Warming Potential / kg CO_2eq	1370	10	2050	610	7	94	8
Terrestrial Acidification / kg SO_2eq.	2.02	$2.47 \text{ x } 10^{-3}$	0.38	2×10^{-1}	$2.13 \text{ x } 10^{-2}$	2.05×10^{-1}	$1.2 \text{ x } 10^{-2}$
Freshwater Eutrophication / kg P eq.	5×10^{-5}	$1.72 \text{ x } 10^{-6}$	5.8×10^{-2}	$7.81 \text{ x } 10^{-6}$	$3.85 \text{ x } 10^{-5}$	$1.49 \text{ x } 10^{-4}$	$1.12 \text{ x } 10^{-5}$
Ozone Depletion / kg CFC-11 eq.	1.38×10^{-13}	$7.37 \text{ X } 10^{-15}$	2.41×10^{-3}	$7.86 \text{ x } 10^{-14}$	$2.78 \text{ x } 10^{-14}$	$3.63 \text{ x } 10^{-10}$	$6.36 \text{ x } 10^{-12}$
Fossil Depletion / kg oil eq.	248	$2.26 \text{ x } 10^{-1}$	10.4	179	1.95	18.7	1.62
Freshwater Ecotoxicity / kg 1,4-DB eq.	2.02×10^{-2}	$6.9 \text{ x } 10^{-5}$	4.3×10^{-1}	1.1×10^{-3}	$3.74 \text{ x } 10^{-1}$	$1.82 \text{ x } 10^{-2}$	$8.28 \text{ x } 10^{-4}$
Human Toxicity / kg 1,4-DB eq.	12.5	$3.47 \text{ x } 10^{-1}$	3.03	$3.15 \text{ x } 10^{-1}$	5.75	16	4.24
Ionising Radiation / kg U235 eq.	1.4	$2.32 \text{ x } 10^{-2}$	0.44	5×10^{-1}	335	6.77	$1.28 \text{ x } 10^{-1}$
Marine Ecotoxicity / kg 1,4-DB eq.	4.91×10^{-2}	$1.09 \text{ x } 10^{-4}$	1.8×10^{-3}	7.9×10^{-3}	$8.4 \text{ x } 10^{-2}$	$3.14 \text{ x } 10^{-1}$	$1.35 \text{ x } 10^{-2}$
Marine Eutrophication / kg N eq.	9.34×10^{-2}	$1.39 \text{ x } 10^{-4}$	0.02	$1.18 \text{ x } 10^{-2}$	$7.49 \text{ x } 10^{-3}$	$7.91 \text{ x } 10^{-3}$	$7.16 \text{ x } 10^{-4}$
Metal Depletion / kg Fe eq.	1.4	$8.2 \text{ x } 10^{-1}$	-6.14	1.41	2.23	38.4	3.16
Natural Land Transformation / m^2	3.88×10^{-2}	$-1.16 \text{ x } 10^{-3}$	n/a	$4.62 \text{ x } 10^{-5}$	$-3.62 \text{ x } 10^{-5}$	$3.89 \text{ x } 10^{-4}$	$-1.11 \text{ x } 10^{-3}$
Particulate Matter Formation / kg PM10 eq.	6.89×10^{-1}	$1.72 \text{ x } 10^{-3}$	0.1	$8.24 \text{ x } 10^{-2}$	$6.93 \text{ x } 10^{-3}$	$6.9 \text{ x } 10^{-2}$	$4.54 \text{ x } 10^{-3}$
Photochemical Oxidant Formation / kg NMVOC eq.	2.23	$2.2 \text{ x } 10^{-3}$	0.45	$3.22 \text{ x } 10^{-1}$	$2.38 \text{ x } 10^{-2}$	$1.82 \text{ x } 10^{-1}$	$1.03 \text{ x } 10^{-2}$
Terrestrial Ecotoxicity / kg 1,4-DB eq.	6.07×10^{-3}	$3.49 \text{ x } 10^{-5}$	3.2×10^{-4}	$1.64 \text{ x } 10^{-4}$	$6.88 \text{ x } 10^{-3}$	$1.11 \text{ x } 10^{-1}$	$1.38 \text{ x } 10^{-3}$
Water Depletion / m^3	42.5	815	4.9	57	6.06	136	7.9

polymers and shown similar levels of benefits when compared with incineration [47]. Furthermore, incineration does not produce a product to retain in the system, so on top of the climate change impact of the disposal, there is a further cost of the production of virgin material to replace the plastic that has been lost from the system.

It could however be argued that incineration has value because energy is generated from the system. However, incineration is an inefficient way (in terms of climate change impacts) of generating electricity as there are many other more climate-friendly options of generating electricity than waste incineration. When disposing of 895 kg of plastic *via* incineration, 5020 MJ of electricity is generated. Table 5 shows a comparison of the climate change impacts of generating 5020 MJ of electricity from a variety of conventional sources in the UK [44].

It becomes apparent that incineration is significantly more damaging to the environment in terms of global warming potential than equivalent methods of generating electricity, including hard coal. If it is understood that coal is undesired within the context of electricity generation because of the high levels of carbon emissions, then it is logical to also state that electricity sourced from waste plastic is also undesirable. It becomes useful if there are no other methods for the disposal of the waste, but as this work demonstrates, new solutions are being demonstrated and applied on an industrial scale. This gives a further rationale for the introduction of new recycling technologies, and improvements to waste separation and sorting to remove residual plastic from refuse-derived fuel.

Conclusion

The environmental impact of reprocessing hitherto unrecyclable waste plastic *via* a novel chemical recycling technology, HTT, has been assessed. The key driver behind the main impacts of this process is the consumption of electricity from the grid. This gives prioritisation for future research on the process to look at the reduction of electricity consumption through the implementation of energy efficiency technologies (e.g. heat exchangers) or looking more broadly from a national perspective at how electricity is generated, although this is an ongoing theme across governments and NGOs. The consumption of gas in the process could also be investigated – could steam generation be more efficiently achieved through electricity rather than gas? However, if that was employed, then a route for the utilisation of the gas generated by HTT would need to be investigated. This could potentially be achieved by condensing the gas into a liquefied natural gas which can be used as a steam cracker feedstock, a route commonly applied within the US. Furthermore, by removing the plastics from incineration, HTT offers a pathway to reduce carbon intensity of the grid by taking the incinerated plastic out of the system and having it replaced with low carbon electricity sources.

The impact in terms of climate change of naphtha produced via HTT is comparable to current fossil chemical feedstock production processes for future plastics (and other hydrocarbon products), presenting circularity options for plastics manufacturing alongside HTT as an end-of-life treatment option. Plastic will need to be disposed of and it is essential that this is conducted in the most environmentally safe way possible. HTT represents up to an 80% reduction in climate change emissions when compared with incineration, the main alternative method of disposal currently used for plastics that cannot be mechanically recycled. Furthermore, unlike incineration, HTT conserves the material within the system, leading to a reduction in consumption of fossil-based resources. Future research in this area should include building system-wide models on recycling to incorporate all of the complementary technologies in a fair manner, taking into account that mechanical recycling, pyrolysis etc. will deal with different feedstocks generating a range of both products and by-products.

It has been considered that incineration has benefits in terms of energy generation. However, given that the incineration of waste plastics to produce electricity generates 50% more CO_2 per MJ than hard coal, it becomes clear that this should no longer be considered as an appropriate method of disposal for our waste materials as it is a sub-optimal method for both the treatment of waste plastics and the generation of electricity. As we move towards a more circular, net zero economy, these technologies should be phased out for more environmentally conscious routes. This therefore shows that the addition of chemical recycling to the end-of-life waste treatment options is essential within the global economy over the current fossil-based production and waste management system, from a combination of benefits in material circularity, reducing global warming potential and resource depletion standpoints.

This work also represents an initial starting point into the LCA of chemically-recycled materials and where the technology fits in the larger recycling landscape and the influence it may have on other recycling systems, as well as investigating the overall impact of recycling materials to achieve a circular economy. Research can also focus on adding extra detail to the model in order to identify specifically the causes of high areas of environmental burden and how the technology can be optimised in order to mitigate them.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10924-023-02792-3.

Author Contribution Both authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Matthew Ozoemena and Stuart Coles. The first draft of the manuscript was written by Matthew Ozoemena and Stuart Coles commented on previous versions of the manuscript. Both authors read and approved the final manuscript. We gratefully acknowledge the support from ReNew ELP, particularly Dr Geoff Brighty and Rosie Smith for their support with primary data generation and helpful discussions regarding the nature of the process.

Funding This research was funded as part of the ReNew Wilton Hydrothermal Upgrading Demonstration Plant project, which is part of the Smart Sustainable Plastic Packaging programme by Innovate UK (project reference 49801).

Data Availability The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

References

1. Tabone MD, Cregg JJ, Beckman EJ, Landis AE (2010) Sustainability Metrics: Life Cycle Assessment and Green Design in Polymers. Environ Sci Technol 44:8264–8269. https://doi.org/10.1021/es101640n
2. Álvarez-Chávez CR, Edwards S, Moure-Eraso R, Geiser K (2012) Sustainability of bio-based plastics: general comparative analysis and recommendations for improvement. J Clean Prod 23:47–56. https://doi.org/10.1016/j.jclepro.2011.10.003
3. Plastics E (2021) Plastics - the Facts (2021)

4. U S Environmental Protection (2010) Municipal Solid Waste Generation, Recycling, and Disposal in the United States : Facts and Figures for 2010.AMBRA GmbH1–12
5. Circular Economy Action Plan for a cleaner and more competitive Europe
6. WRAP (2018) A Roadmap to 2025 - The UK Plastics Pact | WRAP UK. Wrap 11
7. HM Government (2018) Our waste, our resources: a strategy for England. In: HM Goverment
8. A Circular Plastics Economy Strategy for India
9. Ragaert K, Delva L, Van Geem K (2017) Mechanical and chemical recycling of solid plastic waste. Waste Manag 69:24–58. https://doi.org/10.1016/j.wasman.2017.07.044
10. Lange JP (2021) Managing Plastic Waste-Sorting, Recycling, Disposal, and product redesign. ACS Sustain Chem Eng 9:15722–15738
11. Burgess M, Holmes H, Sharmina M, Shaver MP (2021) The future of UK plastics recycling: one bin to rule them all. Resour Conserv Recycl 164:105191. https://doi.org/10.1016/j.resconrec.2020.105191
12. Hong M, Chen EY-X (2017) Chemically recyclable polymers: a circular economy approach to sustainability. Green Chem 19:3692–3706
13. Chemical Recycling Eurrope (2019)Definition of Chemical Reycling
14. Maschmeyer T, Humphreys LJ (2011) Methods for biofuel production
15. Zhou XL, He PJ, Peng W et al (2022) From plastics to methane and carbon spheres: the evolution of pyrolysis products during pyrolysis under autogenic atmosphere. J Anal Appl Pyrolysis 161:105421. https://doi.org/10.1016/j.jaap.2021.105421
16. Lopez G, Artetxe M, Amutio M et al (2018) Recent advances in the gasification of waste plastics. A critical overview. Renew Sustain Energy Rev 82:576–596. https://doi.org/10.1016/j.rser.2017.09.032
17. Green A (2020) Fixing the system: Why a circular economy for all materials is the only way to solve the plastic problem
18. Enkvist P-A, Klevnäs P (2018) The Circular Economy - A powerful force for climate mitigtaion - Full Report.Mater Econ1–7
19. Material Economics (2019) Industrial Transformation 2050 Industrial Transformation 2050 - Executive summary. Focus Catal 2006:8
20. Agora Energiewende and Wuppertal Institute (2019) Climate-Neutral Industry (Executive Summary): Key Technologies and Policy Options for Steel, Chemicals and Cement
21. Davidson MG, Furlong RA, McManus MC (2021) Developments in the life cycle assessment of chemical recycling of plastic waste – a review. J Clean Prod 293:126163. https://doi.org/10.1016/j.jclepro.2021.126163
22. CE Delft (2019) Exploratory study on chemical recycling. Update 2019
23. BASF (2020) ChemCycling: environmental evaluation by Life Cycle Assessment. LCA)
24. Somoza-Tornos A, Gonzalez-Garay A, Pozo C et al (2020) Realizing the potential high benefits of Circular Economy in the Chemical Industry: Ethylene Monomer Recovery via Polyethylene Pyrolysis. ACS Sustain Chem Eng 8:3561–3572. https://doi.org/10.1021/acssuschemeng.9b04835
25. Gear M, Sadhukhan J, Thorpe R et al (2018) A life cycle assessment data analysis toolkit for the design of novel processes – a case study for a thermal cracking process for mixed plastic waste. J Clean Prod 180:735–747. https://doi.org/10.1016/j.jclepro.2018.01.015
26. Khoo HH (2019) LCA of plastic waste recovery into recycled materials, energy and fuels in Singapore. Resour Conserv Recycl 145:67–77. https://doi.org/10.1016/j.resconrec.2019.02.010
27. Jeswani H, Krüger C, Russ M et al (2021) Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. Sci Total Environ 769. https://doi.org/10.1016/j.scitotenv.2020.144483
28. Gracida-Alvarez UR, Winjobi O, Sacramento-Rivero JC, Shonnard DR (2019) System analyses of high-value chemicals and fuels from a Waste High-Density Polyethylene Refinery. Part 2: Carbon Footprint Analysis and Regional Electricity Effects. ACS Sustain Chem Eng 7:18267–18278. https://doi.org/10.1021/acssuschemeng.9b04764
29. Al-Salem SM, Evangelisti S, Lettieri P (2014) Life cycle assessment of alternative technologies for municipal solid waste and plastic solid waste management in the Greater London area. Chem Eng J 244:391–402. https://doi.org/10.1016/j.cej.2014.01.066
30. Alston SM, Clark AD, Arnold JC, Stein BK (2011) Environmental impact of pyrolysis of mixed WEEE plastics part 1: experimental pyrolysis data. Environ Sci Technol 45:9380–9385. https://doi.org/10.1021/es201664h
31. Iribarren D, Dufour J, Serrano DP (2012) Preliminary assessment of plastic waste valorization via sequential pyrolysis and catalytic reforming. J Mater Cycles Waste Manag 14:301–307. https://doi.org/10.1007/s10163-012-0069-6
32. Benavides PT, Sun P, Han J et al (2017) Life-cycle analysis of fuels from post-use non-recycled plastics. Fuel 203:11–22. https://doi.org/10.1016/j.fuel.2017.04.070
33. Demetrious A, Crossin E (2019) Life cycle assessment of paper and plastic packaging waste in landfill, incineration, and gasification-pyrolysis. J Mater Cycles Waste Manag 21:850–860. https://doi.org/10.1007/s10163-019-00842-4
34. Vienescu DN, Wang J, Le Gresley A, Nixon JD (2018) A life cycle assessment of options for producing synthetic fuel via pyrolysis. Bioresour Technol 249:626–634. https://doi.org/10.1016/j.biortech.2017.10.069
35. Barry D, Barbiero C, Briens C, Berruti F (2019) Pyrolysis as an economical and ecological treatment option for municipal sewage sludge. Biomass Bioenergy 122:472–480. https://doi.org/10.1016/j.biombioe.2019.01.041
36. ISO (2006) Environmental Management - Life Cycle Assessment - Principles and Framework (ISO 14040:2006)
37. ISO (2006) Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006)
38. European Commission (2008) Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives. Off J Eur Union L312:1–59
39. BEIS (2020) The Energy White Paper: powering our net Zero Future. Presented to Parliament by the Secretary of State for Business. Energy and Industrial Strategy by Command of Her Majesty
40. European Commission (2006) Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)
41. Department for Environment Food & Rural Affairs (2021) The REACH etc. (Amendment) Regulations 2021
42. European Commission (2008) Waste Framework Directive
43. Teelrn C, Bouter A, Melgar J (2021) Transp Res Part D Transp Environ 97:102897. https://doi.org/10.1016/j.trd.2021.102897. Life cycle assessment of mid-range passenger cars powered by liquid and gaseous biofuels: Comparison with greenhouse gas emissions of electric vehicles and forecast to 2030
44. Sphera Solutions (2021) GaBi: Software and database contents for Life Cycle Engineering
45. Hmiel B, Petrenko VV, Dyonisius MN et al (2020) Preindustrial 14CH4 indicates greater anthropogenic fossil CH4 emissions. Nature 578:409–412. https://doi.org/10.1038/s41586-020-1991-8

46. Wernet G, Bauer C, Steubing B et al (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21:1218–1230. https://doi.org/10.1007/s11367-016-1087-8
47. Sphera Solutions (2021) Life Cycle Assessment of Chemical. Recycling for Food Grade Film