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Tipping points in polymer life cycle greenhouse gas emissions

Stuart Walker ^{*a}, Rachael Rothman ^{b,c}, Antony Ryan ^{b,d}

For decades, polymers have offered a unique combination of low cost and high durability, and are the material of choice for a huge range of applications. In the current energy system, such polymers require the combustion of fossil resources to provide process heat and electricity for manufacture, and release emissions from embodied resources when incinerated. Polymers which are biodegradable or based on biological feedstock avoid some of this resource use, but in some cases have greater energy requirements than fossil polymer equivalents. This work compares life cycle greenhouse gas emissions for pairs of fossil- and biologically-based polymers under various UK electricity, heat and end-of-life treatment scenarios between 2019 and 2040. As specific emissions from electricity and heat supply reduce over the period, life cycle emissions of all polymers fall. Polylactic Acid was found to already have lower emissions than polystyrene in most scenarios. Low-density polyethylene was found to have lower emissions than poly(butylene adipate-co-terephthalate) in all cases to 2040. Both bio-based high density polyethylene and bio-based polyethylene terephthalate were found to have lower emissions than their fossil equivalents at some point between 2019 and 2040, depending on energy and end-of-life scenarios. Identifying and acting on these crossover points offers a route to significant reductions in the emissions of polymers, and even suggests that polymers with net negative emissions can be manufactured by 2040, offering the possibility of greenhouse gas sequestration through polymers made from agricultural waste.

1 Introduction

Between 1950 and 2017, an estimated 8300 million tonnes of plastic was manufactured¹. Plastics are found in almost every aspect of human life, and demand continues to grow. In many cases polymers are more effective and lower cost than alternatives, or allow otherwise impossible products to exist. Many are recyclable, but due to lower cost and greater certainty in material properties, new polymers are often the most economically attractive route. The ubiquity of polymers has negative environmental impacts, particularly if their useful lifetime is short. The ‘plastics problem’ is in fact a plastic waste problem, since the properties which make plastics so useful also make them difficult to manage at the end of their useful lives. The durability of many polymers means that they do not degrade in air or water, but over time will break down into smaller pieces, which can enter food chains. The negative impacts of plastic are exacerbated by the growth in single-use plastics, and the potential for polymers to leak from managed waste streams or be lost as litter. In recent years, plastic has become demonised and its reduction in favour of alternative materials has become a major campaign issue for environmental groups. In an attempt to address these concerns whilst maintaining product function, many polymer manufacturers now offer bio-based polymers, promoted as an environmentally-friendly alternative.

There are fundamentally two opportunities for the incorporation of biological materials or processes into the life cycle of a polymer: (a) by using a biological feedstock to make the product, or (b) by ensuring that the polymer degrades by either a biologically mediated process or otherwise into metabolites at the end of its life. The term ‘Bioplastic’ is generally used to describe either or a combination of the two. Bio-based and fossil-based polymers can each be biodegradable or not biodegradable, so a polymer can occupy any one of four quarters of a matrix of feedstock origin and end-of-life biodegradability. Such a matrix is shown with examples in Figure 1. The term compostable is often used to describe polymers which can be disposed of through biodegradation by incorporating them into mixed biological waste, which will eventually produce a compost product. The presence of other biological matter is necessary for a compostable polymer to degrade in this way, and the term in practice covers a range of degradation timescales and requirements.

This work studies the relative greenhouse gas emissions of plastic manufactured from fossil-based and bio-based feedstocks (the latter known as ‘bioplastics’) within the context of climate change driven by greenhouse gas emissions, and looks at how impacts may change in future as a greater proportion of energy is generated from renewable sources.

1.1 Climate change

The effects of anthropogenic climate change can be seen in the increased severity and frequency of climatic events and unprecedented species loss. Atmospheric greenhouse gas concentration is now over 415 parts per million² and continues to rise. It now appears unlikely that global temperature rise by 2100 will be maintained below the target of 1.5°C above pre-industrial levels recommended by the Intergovernmental Panel on Climate Change (IPCC)³ and stated in the 2015 Paris Agreement. Estimates following the 2021 COP26 meeting suggest that current targets are likely to lead to warming of 2.4°C⁴. Drastic emission reduction schemes will be required to

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	Non-biodegradable	Biodegradable
Bio based	<p>Bio PET</p> <p>Bio HDPE</p> <p>Bio PP</p> <p>Bio PA</p> <p>PEF</p> <p>PTT</p>	<p>PLA</p> <p>PHA</p> <p>Bio-PBS</p> <p>TPS</p> <p>Cellulose</p>
Fossil based	<p>Fossil PET</p> <p>Fossil LDPE</p> <p>Fossil HDPE</p> <p>Fossil PS</p> <p>Fossil PP</p>	<p>PBAT</p> <p>Fossil PBS</p> <p>PCL</p>

Fig. 1 Comparison matrix of common polymers by feedstock origin and biodegradability. Polymers considered in this work are highlighted in colour. PET=Polyethylene terephthalate, HDPE=High-density polyethylene, PP=Polypropylene, PA=Polyamides, PEF=Polyethylene Furanoate, PTT=Polytrimethylene terephthalate, PLA=Polylactic acid, PHA=Polyhydroxyalkanoates, PBS=Polybutylene succinate, TPS=Thermoplastic starch, LDPE=Low-density polyethylene, PS=Polystyrene, PBAT=Polybutylene adipate terephthalate, PCL=Polycaprolactone

32 limit warming to 2°C and even with these, the removal of greenhouse gas from the atmosphere will also be required in order to limit
 33 the worst impacts of climate change.

34 In 2020, fossil fuel electricity generation accounted for 15.4% of total UK greenhouse gas emissions⁵. In common with many
 35 countries, UK grid electricity is generated by a range of sources, including fossil fuel, nuclear and renewable generation. Generation
 36 of electricity using modern combined-cycle gas fired turbines results in greenhouse gas emissions of the order of 460 gCO₂e/kWh⁶,
 37 compared with emissions from renewable sources such as fixed offshore wind of the order of 10 gCO₂e/kWh⁷. The most recent annual
 38 projections of electricity demand and source from the department for Business, Energy and Industrial Strategy (BEIS)⁸, forecasts that
 39 generation from ‘low carbon sources’ (defined therein as renewable, nuclear or Carbon Capture and Storage (CCS) power producers)
 40 will rise from 51% in 2018 to 83% of total UK electricity generation in 2040. The BEIS projections model the impact of policy on
 41 electricity generation using seven scenarios. The central ‘Reference’ scenario assumes central estimates of economic growth and fossil
 42 fuel prices, and includes policies where decisions are sufficiently advanced to allow robust estimates of impact. Six additional scenarios
 43 assume higher and lower fossil fuel prices, economic growth, and policy adoption. Reference scenario projections have been adopted in
 44 this work. The projected emissions of UK electricity generation from 2019 to 2040 are discussed in Section 2.3.

45 Industrial processes account for around 14% of total UK greenhouse gas emissions⁹. Reducing the specific greenhouse gas emissions
 46 of heat provision is a major challenge, as highlighted by BEIS¹⁰. One likely alternative to current heat provision is the use of hydrogen as
 47 a fuel for combustion in place of natural gas. Hydrogen can be produced either by steam methane reforming (SMR), or the electrolysis
 48 of water. Both routes are considered in this work, and discussed in more detail in Section 2.3.

49 1.2 Polymer life cycle

50 Greenhouse gas emissions over the life cycle of a polymer can be divided into three areas: Resource, electricity use, and heat. Since
 51 fossil-based polymers are made directly from a fossil resource, the greenhouse gas contained in the fossil resource is ultimately embodied
 52 in the polymer. The resource has net zero emissions prior to end-of-life treatment, but if a fossil polymer is incinerated, these emissions
 53 are released. A bio-based resource absorbs CO₂ during growth, part of which is used for respiration and part of which is stored in the
 54 plant, meaning that a bio-based resource can have negative embodied CO₂ prior to end-of-life treatment. If a bio-based polymer is
 55 incinerated, these negative emissions are lost and net resource emissions are zero.

56 In addition to resource emissions, the processes of extraction, refining and polymer manufacture require inputs of heat and electricity
 57 in both fossil and biological cases. In the biological case, refinement from plant to chemical raw material is also required. The amount
 58 of heat and electricity required in each case varies with differences in specific processing and operating temperatures, defined by the
 59 resource and the properties of the final polymer. Emissions related to the heat and electricity processes are a function of the energy
 60 requirement and the emission intensity of the source. End of life treatment also has heat and electricity requirements, which vary
 61 depending on the method used and the product being treated, and direct emissions from polymers when incinerated or composted. The
 62 incineration and composting processes cause the release of some or all of the embodied greenhouse gas in a polymer at the end of life
 63 (Table 2 and Section 2.4).

64 If the sum of resource emissions and emissions related to heat and electricity are greater than zero, it has net life cycle emissions.

65 This can be the case even if a biological resource is used and the polymer is not incinerated, if heat and electricity emissions exceed the
66 net negative resource emissions. However, as energy sources change, emissions related to heat and electricity processes may fall and
67 this balance may change.

68 In order to minimise emissions required to produce a polymer suitable for a particular purpose, the full life cycle must be considered,
69 including the emissions intensity of the energy used for manufacture and end-of-life treatment. As emissions linked to electricity and
70 heat fall due to the defossilisation of energy networks, a polymer use case which is currently best satisfied by a fossil polymer may in
71 future be best satisfied by a bio-based polymer.

72 In order to consider the impact of the growth in bio-based and biodegradable plastics within the context of climate change and
73 the gradual defossilisation of energy supply, this work describes the calculation of net environmental impact for a series of comparable
74 fossil-based and bio-based polymers over their full life cycle. Indicative profiles of cumulative emissions over polymer life cycle for
75 fossil-based and bio-based polymers are illustrated in Figure 2. These indicative profiles show the potential for the accumulation of
76 positive and negative emissions over the major stages of each polymer type life cycle, and the potential change in future due to energy
77 defossilisation.

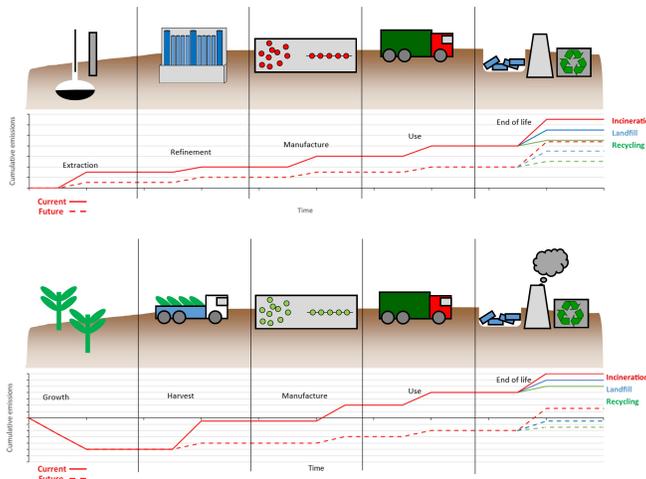


Fig. 2 Indicative cumulative life cycle emissions profiles for fossil-based (top) and bio-based (bottom) polymers.

78 2 Methods

79 This study considers the lifetime emissions of four pairs of comparable fossil-based and biologically-based or biodegradable polymers
80 to understand the greenhouse gas emissions of each, including embodied carbon content of bio-based polymers and the impact of
81 end-of-life treatment on total lifetime emissions. The study calculates how these emissions will change with reductions in the specific
82 emissions of electricity generation and heat supply.

83 2.1 Life Cycle Assessment

84 Life cycle assessment (LCA) is a widely-used technique to understand the environmental impact of a product, process or system. Here
85 emissions of polymers are compared over the full life cycle (commonly called a 'Cradle-to-grave' scope assessment). The functional unit
86 was 1 kilogram of polymer, selected to ensure that the two polymers in each pair are functionally comparable. Defining a functional unit
87 based on a final product function would have unavoidably introduced a skew towards the most suitable polymer for the selected product
88 (for example, if a functional unit of one drinks bottle had been selected, this would be more efficiently achieved by PET or HDPE, and
89 would therefore disadvantage other polymers). Results were calculated for polymer greenhouse gas emissions in kilograms of carbon
90 dioxide equivalent (kgCO_2e) using the IPCC 100 year Global Warming Potential impact assessment method. SimaPro and openLCA
91 software was used for the initial study, with Microsoft Excel used to calculate future projections. Resource and process emissions
92 intensity data was taken from the Ecoinvent 3.7.2 database¹¹, European Life Cycle Database version 3.2¹², United States Life Cycle
93 Inventory (USLCI)¹³, and a series of publications. Data sources in each case are described in the following sections, and full data tables
94 are given in supplementary material.

95 2.2 Polymer pairs

96 Polymer pairs comprise two polymers with identical or very similar (sufficiently similar that one could directly replace another in its
97 most common application) properties, the first being a non-biodegradable fossil-based polymer, and the latter an alternative which is
98 either bio-based or biodegradable, or bio-based and biodegradable. Due to the infancy of the bio-based polymer industry and the current

99 high cost of bio-based polymers relative to fossil-based polymers, cost was not defined as a property when developing polymer pairs.
100 The four pairs considered here are described in the following sections. All polymers were assumed to be manufactured in the UK using
101 the method and feedstock most common or most suitable for the UK. End of life treatment processes were based on UK information (as
102 in Section 2.4).

103 2.2.1 Pair 1: Fossil-based polyethylene terephthalate (fPET) and bio-based polyethylene terephthalate (bPET)

104 Polyethylene terephthalate (PET) is most commonly used for the manufacture of transparent bottles. It is manufactured from two
105 ingredients, terephthalic acid (TA) and ethylene glycol (EG). Both products can be obtained from fossil resources by the chemical
106 cracking of fossil fuels, or by the refinement of biological resources, meaning that PET can be fully fossil-based, partially fossil-based
107 in two ways, or entirely biologically-based. Consequently, this 'pair' actually included four polymer formulations. Abbreviations, as
108 given in Table 1, are sometimes used to describe the four types of PET. Of the two ingredients, TA is more technically challenging to
109 produce from biomass sources, meaning that many previous products marketed as bio-based PET, such as the first generation Coca-Cola
110 'Plant Bottle'¹⁴, in fact used bio-based EG and fossil-based TA^{15 16}. Fossil-based and partially or fully biologically-based PET can be
mechanically and chemically recycled at the end of life.

Table 1 Abbreviations used to describe raw material sources of four types of polyethylene terephthalate (PET)

Abbreviation	EG source	TA source
ffPET	Fossil-based	Fossil-based
fbPET	Bio-based	Fossil-based
bfPET	Fossil-based	Bio-based
bbPET	Bio-based	Bio-based

111
112 In the ffPET case, both fundamental ingredients used to make PET are derived from fossil resources. Xylene mixture is produced
113 from crude oil extraction, and is then separated to give paraxylene. This is oxidised to give terephthalic acid. Ethylene glycol is produced
114 by petrochemical processing of crude oil to give ethylene, which is then oxidised into ethylene oxide, and finally hydrated into ethylene
115 glycol.

116 Biologically-based ethylene glycol was assumed to be derived from wheat straw, as in previous work^{17 15}. In this case, the bio-
117 logical source is harvested and delivered to a pretreatment facility, where the sugars it contains are fermented into ethanol. This is
118 dehydrated to produce ethylene, which can then be oxidised to give ethylene oxide. Finally, hydrating this produces ethylene gly-
119 col^{18 19}. Biologically-based purified terephthalic acid was assumed to be produced from forest residues. First, the residues are processed
120 to hydrolyzate, fermented to make isobutanol, then paraxylene¹⁶ which is used in place of fossil-based xylene in the terephthalic acid
121 manufacturing process²⁰. Life cycle models in this study assumed UK feedstocks, electricity and heat sources.

122 EG and TA are made into the step-growth polymer by direct esterification, with the elimination of water, to produce amorphous
123 PET granules for all four types of PET. These are then prepared for applications, such as the production of PET bottles, by solid-state
124 polycondensation to increase the chain length and optimise the processing properties.

125 2.2.2 Pair 2: Polystyrene (PS) and polylactic acid (PLA)

126 In the takeaway food sector, biologically-based alternatives to PS packaging have been developed and are becoming popular with
127 environmentally-conscious consumers. The most common of these is polylactic acid (PLA). PLA is formed by the fermentation of
128 dextrose from milled biological material to form lactic acid, which is converted to the lactide dimer then ring-opening polymerisation
129 used to produce polylactide. While PS is fossil-derived and non-biodegradable, PLA is a bio-based biodegradable polymer, occupying
130 the upper right of the conceptual square shown in Figure 1.

131 PLA was assumed to be manufactured in the UK from global mixed maize grain, using manufacturing process data published by
132 NatureWorks²¹ and contained in the Ecoinvent 3.7.2 database¹¹, with modifications to represent the UK manufacturing case.

133 PS manufacturing was based on production data from PlasticsEurope^{20 22} and Ecoinvent 3.7.2¹¹, which suggests heat is the major
134 contributor to total emissions. Biomass and hydroelectric sources were replaced with UK heat and grid electricity in the life cycle
135 models.

136 2.2.3 Pair 3: Low-density polyethylene (LDPE) and poly(butylene adipate-co-terephthalate) (PBAT)

137 Low-density polyethylene (LDPE) is formed from the polymerisation, using a high pressure free radical polymerisation process, of
138 ethylene produced from the cracking of naphtha refined from crude oil. Poly(butylene adipate-co-terephthalate) (PBAT) is a polymer
139 made by the copolymerisation of 1,4 butane diol with adipic acid and terephthalic acid (TA above). PBAT combines the biodegradability
140 of an aliphatic polyester and the mechanical properties of an aromatic polyester. It is one of the few polymers which is fossil-based but
141 also biodegradable. PBAT is characterised by high flexibility and high elongation at break, making it suitable for applications such as
142 packaging, including bags, food containers and food wrapping, and therefore making it an alternative to LDPE in many applications²³.

143 LDPE was based on previous studies²⁴ and PlasticsEurope data²⁰ via Ecoinvent 3.7.2¹¹, with biomass and hydroelectric energy
144 sources replaced by UK heat and grid electricity. PBAT was assumed to be made from purified terephthalic acid as in the fossil-based

145 PET case, adipic acid based on Swiss data²⁵ and butane 1,4-diol based on data from the Ecoinvent 3.7.2 database^{11,26}. Life cycle
146 models were modified to use UK electricity and heat sources.

147 2.2.4 Pair 4: High-density polyethylene (HDPE) and Bio-based High-density polyethylene (bio-HDPE)

148 High-density polyethylene (HDPE) is often used in the UK for a range of packaging applications. It is manufactured by first refining
149 crude oil to produce naphtha, then cracking naphtha to produce ethylene, which is polymerised to high density polyethylene. This process
150 was assumed to take place in the UK and was based on previous studies²⁴ and data from PlasticsEurope²⁰ included in the Ecoinvent
151 3.7.2 database¹¹. Bio-based HDPE is made using a similar process, whereby fossil-derived ethylene is replaced with ethylene derived
152 from biological sources. Ethylene is commonly produced from sugarcane ethanol, however in this case UK wheat straw was assumed
153 to be the feedstock, with all subsequent processes undertaken in the UK. Supporting data was taken from previous studies^{17,15} and UK
154 electricity and heat sources were used.

155 2.3 Defossilisation of electricity and heat

156 Defossilisation of the electricity network (i.e. the gradual reduction in the emissions of electricity generation as more low emission
157 sources are adopted instead of fossil-fuel based sources) was based on the BEIS 'Reference' projection for the UK as described in Section
158 1.1. From a 2019 starting point of 0.1557 kgCO₂/kWh, the overall trend is a falling emissions factor, though there are increases from
159 the previous year seen in 2024 and 2028. The final emissions factor given in the projection is 0.0666 kgCO₂/kWh in 2040. At the time
160 of writing, actual UK grid emissions are somewhat higher than the 2019 figure given in the Reference scenario, so transitions which rely
161 on grid defossilisation are likely to occur later than those predicted by this data. Applying a linear trend suggests an offset of around 10
162 years (i.e. the UK is likely to reach the BEIS Reference intensity for 2019 in 2029).

163 At present, the majority of heat used in polymer production is generated by the combustion of fossil-derived 'natural' gas. In
164 addition to this, two further scenarios were also considered in life cycle models: The replacement of this gas with hydrogen generated
165 from the reformation of methane using the steam methane reforming (SMR) process, and the replacement of natural gas with hydrogen
166 generated by electrolysis. These methods were considered over the same time period as electricity defossilisation. The use of heat
167 generated by burning natural gas was assumed to have emissions of 0.2915 kgCO_{2e}/kWh, which was assumed to remain constant over
168 the time period. Hydrogen production by SMR uses a small amount of electricity, and the changing electricity emissions factor was
169 applied to account for the changing impact of this method. Hydrogen produced by SMR was assumed to have a 2019 emissions factor
170 of 0.2820 kgCO_{2e}/kWh, and projected to fall to 0.2813 kgCO_{2e}/kWh by 2040. The production of hydrogen from water electrolysis
171 does not use a fossil fuel feedstock, but does have a significant electricity use. The emissions of heat produced in this way in 2019 were
172 assumed to be 0.2303 kgCO_{2e}/kWh, and due to falling emissions of electricity production were forecast to be 0.0986 kgCO_{2e}/kWh in
173 2040. Annual emissions per kWh of electricity generation and heat production by three methods are shown in Figure 3.

174 2.4 End of life treatment

175 The emissions related to the end-of-life treatment of a polymer have two constituent parts: The process emissions of the treatment and
176 the polymer emissions released at end of life. If a polymer is recycled, process emissions are caused, but emissions from the polymer
177 are avoided since the embodied greenhouse gas is not released.

178 Of the eight polymers considered, six (fHDPE, bHDPE, fPET, bPET, PS and LDPE) are best suited to recycling. The remaining two
179 (PBAT and PLA) are designed to be compostable. Actual plastic recycling rates differ between country and polymer type, and are often
180 lower than theoretically possible²⁷. To represent a range of recycling rate cases, 2.7% , 50% and 100% rates were used. UK, EU
181 and global recycling rates for plastic are estimated at around 41%. 2.7% was the lowest reported polymer recycling rate reported in
182 PlasticsEurope data²⁰, so was selected as a minimum.

183 Where recycling was assumed, process data from the Ecoinvent 3.7.2 database¹¹ and supporting data from Defra²⁸ was used.
184 0.6kWh of electrical energy was assumed to be required to recycle 1kg of waste polymer into recycled polymer. Demand for recycled
185 polymers was not considered; it was assumed that recycled polymer produced would be used in place of virgin polymer in downstream
186 products. The same rates as in the recycling case were used as composting rates for compostable polymers. Data for the composting
187 process was taken from work by Carbotech²⁹. In order to process 1kg of waste compostable polymer, an electricity requirement of
188 0.012kWh was assumed to be required. The process was assumed to produce 0.4kg of organic matter per kilogram of polymer, and
189 to release 0.22kg CO₂, 0.001kg Methane, 0.35kg water and small amounts of ammonia, dinitrogen monoxide and hydrogen sulfide.
190 The remaining mass (0.0185g) of residual waste was treated in the same way as the residual waste not recycled or composted in each
191 scenario. During the composting process, a portion of the embodied CO₂ in the polymer is released to atmosphere (C_{loss}), and a portion
192 is bound in the soil. The relative released and bound portions vary with material, composting system type and conditions. Literature
193 review on the subject³⁰ suggests C_{loss} values of 0.4 to 0.83, with most studies suggesting 0.5 to 0.6. A value of 0.55 was adopted for
194 this study and used to calculate composting values given in Table 2. Since PLA and PBAT have the same carbon, hydrogen and oxygen
195 ratio, the values of composting emissions are the same.

196 In the 2.7% and 50% rate scenarios, residual waste was modelled as being treated by incineration or landfill. Incineration processes

197 were based on European data, which was modified to represent the UK case. The incineration of 1kg of polymer was found to release
 198 between 2.07 and 3.20 kgCO₂e per kilogram of polymer (Table 2), and to generate 0.027MJ of electricity, which would offset between
 199 0.1514 and 0.065kgCO₂e between 2019 and 2040. The landfill of 1kg of polymer was found to release between 0.0906 and 0.135
 200 kgCO₂e per kilogram of polymer (Table 2). Supporting data was taken from Ecoinvent 3.7.2¹¹, based on municipal incineration and
 201 landfill in Europe, with necessary modifications to represent the UK.

Table 2 Total (process and released biogenic) greenhouse gas emissions for end-of-life treatment of residual polymers by incineration, landfill and composting

Polymer type	Method	Emissions (kgCO ₂ e/kg polymer)
PET (bPET, fPET)	Landfill	0.0906
	Incineration	2.07
PS	Landfill	0.135
	Incineration	3.20
PE (bHDPE, fHDPE, LDPE)	Landfill	0.129
	Incineration	3.03
PLA, PBAT	Landfill	0.102
	Incineration	2.38
	Composting	1.31

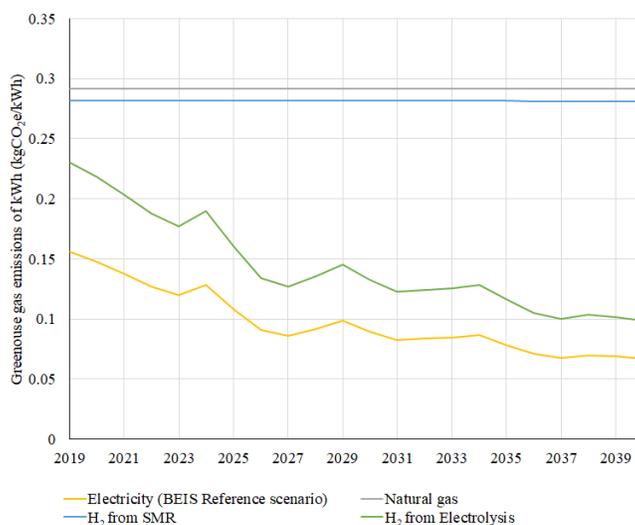


Fig. 3 Greenhouse gas emissions per kWh of electricity (BEIS Reference scenario projection⁸) and of heat production using natural gas combustion, hydrogen generated by steam methane reforming, and hydrogen generated by electrolysis.

202 3 Results

203 3.1 Data Quality

204 Previous work³¹ highlights the importance of comparability between LCA studies with a focus on bio-based and fossil-based polymers.
 205 Studies should ideally use the same boundaries, but must at least be transparent. One method of achieving this is through the adoption
 206 of the Product Environmental Footprint (PEF) method and the calculation of a data quality value. The value is the mean score from six
 207 categories (Completeness, Methodological appropriateness and consistency, Time representativeness, Technological representativeness,
 208 Geographical representativeness, Parameter uncertainty), each scored from 1 to 5 using criteria from the PEF documentation³². Final
 209 scores of below 1.6, below 2.0, below 3.0, and below 4.0 signify excellent, very good, good and fair data quality respectively, with any
 210 result over 4.0 signifying poor data quality. Data quality in the present study was calculated to be 2.0 (very good).

211 Other aspects of the PEF (Goal & Scope definition, Multifunctionality hierarchy, Choice of impact assessment methods, Classification
 212 & characterisation, Interpretation of results, Reporting element requirements, use of relevant Category Rules) were fully or partially
 213 met, using the definitions of partial compliance defined in previous work³¹.

214 3.2 Cradle-to-gate

215 Throughout the results section, reference to a year is based on the projected energy intensity according to the BEIS reference scenario.
 216 As described in Section 2.3, current energy intensity is approximately 10 years behind that in the projection, so dates referred to are

217 likely to be approximately 10 years ahead of actual dates.

218 The proportion of resource, heat and electricity required, and the total emissions attributable to each, varies between polymers.
219 Figure 4 shows the total cradle-to-gate CO₂ uptake and emissions and the relative attribution for each of the eight polymers introduced
220 in Section 2.2, based on 2019 emissions factors and heat provided by the combustion of natural gas.

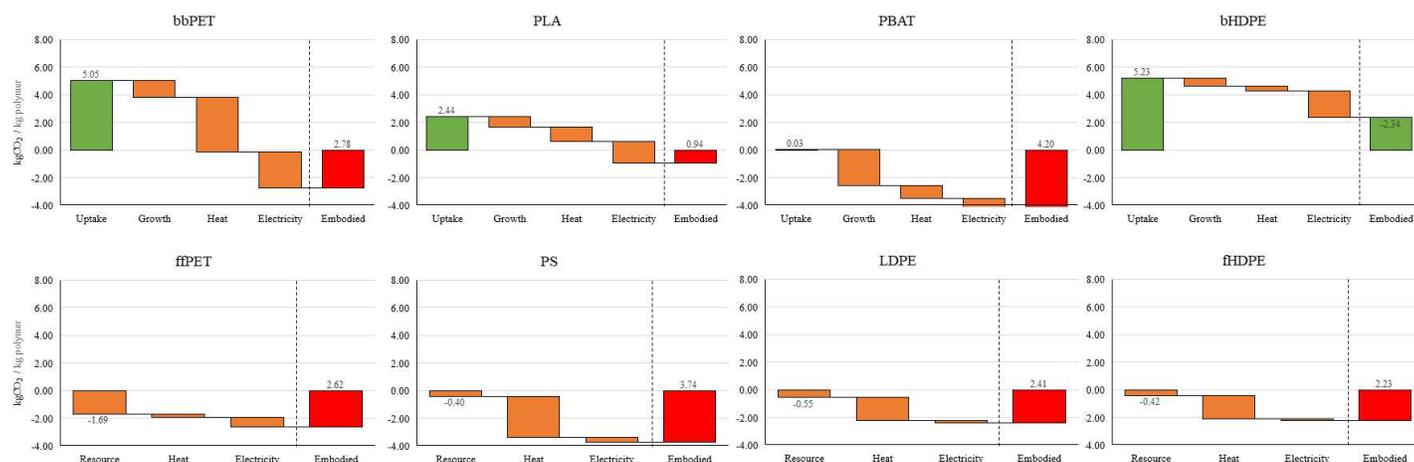


Fig. 4 Cradle-to-gate greenhouse gas emissions per kg of final polymer, showing the contribution of (in bio-based cases) CO₂ uptake, plant growth, heat and electricity or (in fossil-based cases) CO₂e in the resource, heat and electricity, and in each case the net CO₂e embodied in the polymer. Based on heat supplied by gas and 2019 electricity emission intensity.

221 All fossil-based polymers have more than 2kg embodied greenhouse gas per kg of polymer over this cradle-to-gate scenario. Two
222 bio-based polymers (PBAT and bbPET) also have more than 2kg embodied greenhouse gas, with the highest value polymer being PBAT,
223 with 4.20 kgCO₂ per kilogram of polymer. PLA has the second lowest embodied greenhouse gas of all polymers at 0.94 kgCO₂ per
224 kilogram of polymer. bHDPE is the only polymer to show net negative cradle-to-gate embodied greenhouse gas, with a net uptake of
225 2.34 kgCO₂ per kilogram of polymer. This is largely due to the high initial uptake during the growth of the wheat straw used to make
226 this polymer, meaning that it absorbs a relatively large amount of CO₂ during the growth phase. bHDPE was calculated to absorb 5.23
227 kgCO₂ during feedstock growth, which is significantly higher than the absorption of other bio-based polymers (bbPET: 5.05 kgCO₂,
228 PLA: 2.44 kgCO₂, PBAT: 0.03 kgCO₂), meaning that even after plant growth use of 0.58 kgCO₂ and heat and electricity emissions of
229 0.4 and 1.92 kgCO₂e respectively, a portion of the initial absorption remains.

230 Comparison with results of other studies is difficult due to differences in scope, input data sources and impact assessment method.
231 For instance, Chen et al¹⁶ estimated cradle-to-gate emissions of bPET and fPET of 4.14 and 4.74kgCO₂e/kg respectively in comparison
232 to 2.2 and 2.35kgCO₂e/kg in this study, but the former study includes the manufacture of polymer into bottles, is based on USA data, and
233 uses the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI v2.1) Impact Assessment methods
234 designed by the U.S. Environmental Protection Agency, in lieu of the IPCC 100 year Global Warming Potential impact assessment method
235 employed here.

236 3.3 Defossilisation of heat and electricity

237 Applying the defossilisation scenarios described in Section 2.3 to the results in Figure 4 allows the projected change in net cradle-to-gate
238 emissions from 2019 to 2040 to be calculated for each polymer. As the specific emissions of electricity supply fall, the specific emissions
239 of each polymer fall annually in proportion to the level of total emissions derived from electricity. This means that in polymers where
240 electricity supply makes up a large proportion of total emissions, such as bbPET, PLA, and bHDPE, the total emissions reduction is more
241 significant than in polymers with a small emissions contribution from electricity supply, such as PS or LDPE. Similarly, when heat is
242 provided by gas or hydrogen via steam methane reforming, the emissions change is small (due to the small contribution of electricity
243 to the total emissions of these processes), but when heat is provided by hydrogen produced by the electrolysis of water, the change
244 in emissions is more significant. In some bio-based polymer cases, the reduced heat- and electricity-derived emissions per kilogram
245 of polymer are lower than the portion of absorbed CO₂ embodied in the polymer, meaning that over the cradle-to-gate scope, these
246 polymers have negative emissions. This occurs in the bbPET case, which has negative cradle-to-gate emissions if manufactured using
247 heat from hydrogen by electrolysis during 2023 and after 2024. This effect is also seen in the same scenario for the manufacture of PLA.

248 3.4 Cradle-to-grave

249 The cradle-to-gate scenarios described in Section 3.3 were developed into full life cycle scenarios by considering the end-of-life treatment
250 of each polymer. Only a small number of the 1800 total cases modelled are presented here. These results focus on comparison within

Table 3 Comparison of potential to reach Greenhouse gas (CO₂e) neutrality before 2040 based on projected electricity defossilisation by polymer type, heat source and end-of-life treatment. Year indicates the first whole year of net emissions below zero. Electricity supply in all cases assumes defossilisation as per the BEIS Reference scenario. 'EOL rate' refers to composting for PLA and PBAT and recycling for all other polymers. Where the treatment of residual waste alters the year of CO₂ neutrality, the alternative process is shown as '(L)' for landfill and '(I)' for incineration. Where no brackets are used, the year stated applies to both methods of residual waste treatment.

Heat source	EOL rate	fbPET	bbPET	PS	PLA	LDPE	PBAT	fHDPE	bHDPE
Gas	2.7%	-	-	-	-	-	-	-	Pre-2019 (L)
	50%	-	-	-	-	-	-	-	Pre-2019 (L)
	100%	-	-	-	-	-	-	-	Pre-2019
H ₂ from SMR	2.7%	-	-	-	-	-	-	-	Pre-2019 (L)
	50%	-	-	-	-	-	-	-	Pre-2019 (L)
	100%	-	-	-	-	-	-	-	Pre-2019
H ₂ from Electrolysis	2.7%	-	2035(L)	-	2025(L)	-	-	-	Pre-2019 (L)
	50%	-	2035(L), 2035(I)	-	2026(L), 2036(I)	-	-	-	Pre-2019 (L)
	100%	-	2026	-	2030	-	-	-	Pre-2019

251 pairs to estimate the swap-over date and on the question of whether bio-based polymers can achieve net negative emissions.

252 Table 3 highlights which polymers reach net negative emissions under each end-of-life treatment rate, and the manufacturing year
253 from which this is achieved.

254 **3.4.1 Pair 1: Fossil-based polyethylene terephthalate (fPET) and Bio-based polyethylene terephthalate (bPET)**

255 In general, bio-based PET emissions fall more steeply over time than those of fossil-based PET, due to the greater proportion of their
256 total emissions derived from electricity and heat. Figure 5 shows total life cycle emissions including various end-of-life scenarios for
257 fully fossil-based and fully bio-based PET, based on heat provided by gas and forecast rates of electricity defossilisation. For recycling
258 rates of 2.7% or 50% where residual waste is sent to landfill, or for recycling rates of 100%, crossover points occur in 2025, after which
259 bio-based PET has lower emissions than fossil-based PET. If residual waste is incinerated, at a recycling rate of 2.7% fossil-based PET
260 always has lower emissions than bio-based PET (over the time period considered). If residual waste is incinerated, at a recycling rate of
261 50%, bio-based PET has lower emissions than fossil-based PET after a crossover point in 2030.

262 As shown in Table 3, if heat from gas is replaced with heat from hydrogen generated by electrolysis, bio-based PET with emissions
263 below zero can be achieved in 2035 at a recycling rate of 2.7% (only if residual waste is disposed of in landfill) or 50% (with residual
264 waste sent to landfill or incinerated), and in 2026 with a recycling rate of 100%.

265 Based on gas heat, 2019 electricity emissions and 2.7% recycling with residual waste incineration, fossil-based PET life cycle emis-
266 sions were found to be 4.32kgCO₂e/kg polymer. Due to the relatively low electricity use, fossil-based PET emissions fall only slightly
267 over the 2019 to 2040 time period, in this case to 4.11kgCO₂e/kg polymer by 2040 if gas or hydrogen from SMR are used, and from
268 4.31 to 3.78kgCO₂e/kg polymer if hydrogen from electrolysis is used. Increasing recycling rates reduce the life cycle emissions of
269 fossil-based PET, with ultimate best case emissions of 1.80kgCO₂e/kg polymer in 2040, provided heat is generated by hydrogen from
270 electrolysis, and 100% recycling is achieved.

271 If partially bio-based PET is used instead of fully bio-based PET, total emissions fall between those of the fully bio-based and fully
272 fossil-based products. In the fbPET case (Table 1), which uses fossil-based purified terephthalic acid (TA) and bio-based ethylene glycol
273 (EG), emissions are lower than in the bbPET case, which uses bio-based TA and fossil-based EG.

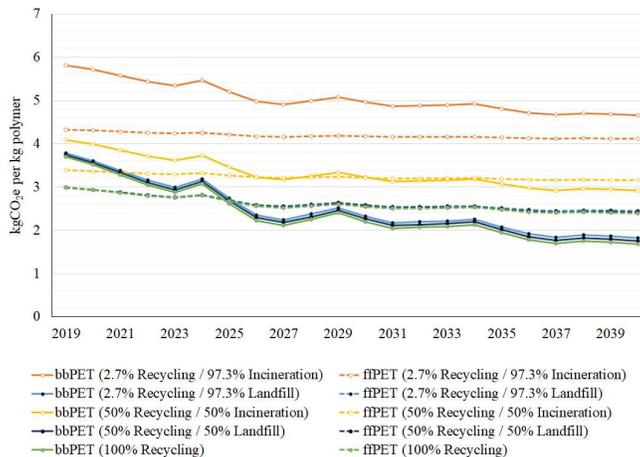


Fig. 5 Cradle-to-grave greenhouse gas emissions for all fully bio-based PET and fully fossil-based PET cases. Emissions per kg of final polymer with three recycling rates and two residual waste cases. Heat supplied by gas in all cases.

274 3.4.2 Pair 2: Polystyrene (PS) and polylactic acid (PLA)

275 Data for polystyrene suggests a large part of total emissions are derived from heat. Consequently, changes in emissions due to reducing
276 electricity grid fossil fuel intensity are relatively small when heat is derived from gas or hydrogen generated by SMR, with total emis-
277 sions changing by only around 2% between 2019 and 2040 in either case, but are sensitive to the change to hydrogen generated by
278 electrolysis. PS emissions are lowest when hydrogen generated by electrolysis is used with high recycling rates. In the 100% recycling
279 rate case with heat provided by hydrogen from electrolysis, 2040 PS emissions are 2.07kgCO₂/kg polymer. In the 100% recycling case
280 with heat provided by gas (as shown in Figure 6, the lowest 2040 PS emissions are 3.59kgCO₂/kg polymer.

281 The contribution of electricity to total emissions in the PLA case is greater than in the PS case, hence defossilisation of electricity
282 has a greater impact on lifetime emissions. If heat is provided by gas or hydrogen from steam methane reforming, PLA cannot achieve
283 emissions below zero, however PLA can achieve life cycle emissions below zero in four end-of-life cases when heat is provided by
284 hydrogen generated using electrolysis (Table 3). In this case with 100% composting or 2.7% composting with residual waste sent
285 to landfill, this occurs from in 2030 or 2025 respectively. In the 50% composting cases, this is achieved in 2026 if residual waste is
286 sent to landfill, or in 2036 if residual waste is incinerated. The emissions associated with incineration and composting mean that the
287 lowest emission cases for PLA are those with the greatest use of landfill end-of-life treatment, and with heat provided by hydrogen from
288 electrolysis. With 2.7% composting and 97.3% of waste sent to landfill, PLA has emissions of -1.12kgCO₂/kg polymer in 2040, if heat is
289 provided by hydrogen produced from electrolysis. In the same heat scenario, 100% composting gives total emissions of -0.946kgCO₂/kg
290 polymer in 2040.

291 It is notable that emissions below zero are achieved later when greater proportions of landfill are replaced by composting, but
292 earlier when greater proportions of incineration are replaced by composting. This is because composting emissions are less than those
293 of incineration but greater than those of landfill treatment. The impact of defossilisation on total emissions of both PLA and PS are
294 illustrated in Figure 6. The results shown illustrate emissions when both polymers are manufactured using heat supplied by gas.

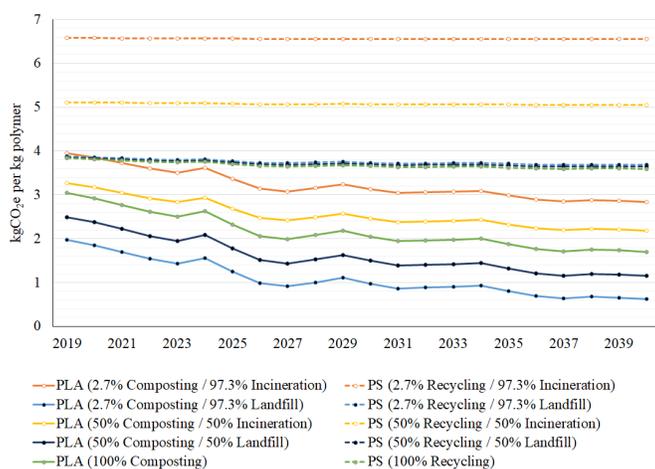


Fig. 6 Cradle-to-grave greenhouse gas emissions for PS and PLA. Emissions per kg of final polymer with three recycling / composting rates and two residual waste cases. Heat supplied by gas in all cases.

295 3.4.3 Pair 3: Low-density polyethylene (LDPE) and poly(butylene adipate-co-terephthalate) (PBAT)

296 Neither polymer in pair 3 was calculated to achieve greenhouse gas emissions below zero in any of the cases considered. In some cases,
297 LDPE was found to have lower emissions than PBAT; in both the 100% recycling case and the 50% recycling case with residual waste
298 sent to landfill, emissions from LDPE were lower than any of the PBAT cases considered.

299 LDPE with 50% recycling and residual incineration was found to have lower emissions than any PBAT case until a crossover point
300 in 2025, after when PBAT with 2.7% composting and residual landfill has lower emissions. After 2038, PBAT with 50% composting
301 and residual landfill also has lower emissions than LDPE with 50% recycling with residual incineration. No PBAT case ever has lower
302 emissions than LDPE with the equivalent end-of-life treatment over the time period considered. However, crossovers could be expected
303 over a longer timeframe since PBAT emissions fall more steeply than those of LDPE, and in 2040, PBAT with 2.7% composting and
304 residual incineration has very similar emissions to LDPE with 2.7% recycling and residual incineration.

305 The lowest emission case for LDPE is when heat is produced by hydrogen from electrolysis and 100% of waste is recycled. In
306 this case, LDPE reaches greenhouse gas emissions of 1.55 kgCO₂e/kg polymer in 2040. In the same case with heat provided by gas,
307 emissions are 2.31 kgCO₂e/kg polymer in 2040.

308 The lowest emission case for PBAT is also when heat is produced by hydrogen from electrolysis, but since emissions from landfill
309 are lower than those from composting, overall lowest emissions are from the case with 2.7% composting and 97.3% landfill. With heat

310 provided by hydrogen from electrolysis, 2040 emissions in this case are 2.46 kgCO₂e/kg polymer, and 4.10 kgCO₂e/kg polymer with
 311 heat provided by gas. Emissions for both polymers with heat provided by hydrogen from electrolysis are illustrated in Figure 7.

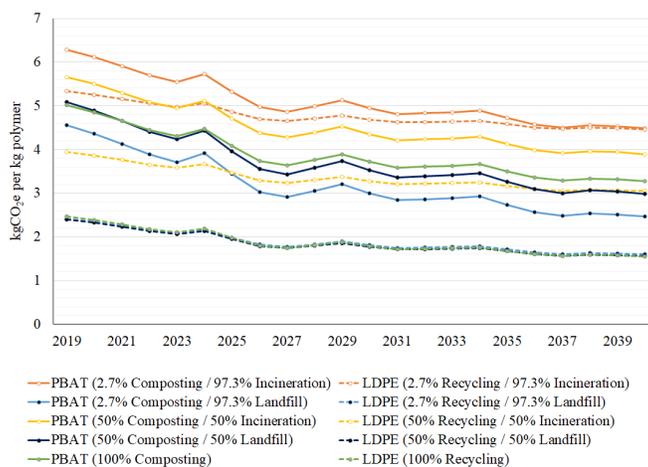


Fig. 7 Cradle-to-grave greenhouse gas emissions for LDPE and PBAT. Emissions per kg of final polymer with three recycling rates and two residual waste cases. Heat supplied by hydrogen from electrolysis in all cases.

3.4.4 Pair 4: Fossil-based High-density polyethylene (fHDPE) and Bio-based High-density polyethylene (bHDPE)

312 The large uptake value and relatively low heat requirements of bio-based HDPE (Figure 4) mean its total emissions are heavily influenced
 313 by the end-of-life treatment method. If residual waste is incinerated, bHDPE with 2.7% recycling rate has higher emissions than fossil-
 314 based HDPE in the same case, because of the extra energy required to produce ethylene from biomass, regardless of heat supply. If
 315 50% recycling rates are achieved, bHDPE has lower emissions than fHDPE, but in all cases these are above zero. With heat provided
 316 by gas, fossil HDPE has emissions in 2040 of between 5.08 and 2.18 kgCO₂e/kg polymer, and bHDPE has emissions of 5.43 and 1.09
 317 kgCO₂e/kg polymer for 2.7% and 50% recycling rates respectively, with residual incineration.

318 When recycling with residual waste sent to landfill or 100% recycling is used, bio-based HDPE is the only polymer projected to
 319 achieve net negative emissions in cases with heat produced by gas or by hydrogen generated by steam methane reforming, as shown
 320 in Table 3. This polymer pair does not exhibit any crossover points because in these cases bHDPE emissions are below zero at forecast
 321 2019 grid electricity emission levels. When heat is supplied by gas, bHDPE with either 2.7% recycling or 50% recycling (with residual
 322 waste sent to landfill) or 100% recycling has 2019 emissions of between -1.97 and -2.13 kgCO₂e/kg polymer. If heat is provided by
 323 hydrogen from steam methane reforming, 2019 emissions are between -1.92 and -2.08 kgCO₂e/kg polymer, and if heat is provided by
 324 hydrogen from electrolysis, 2019 emissions are between -1.97 and -2.47 kgCO₂e/kg polymer. All values fall over time to 2040 levels of
 325 between -3.13 and -3.34, -3.08 and -3.29, and -3.26 and -3.62 kgCO₂e/kg polymer for heat from gas, hydrogen produced from steam
 326 methane reforming, and hydrogen produced by electrolysis respectively. The case using hydrogen generated by electrolysis is illustrated
 327 in Figure 8.

4 Discussion

4.1 Best and current case comparison

330 Figure 9 shows a comparison of the emissions of each of the eight polymers discussed in this work over the 2019-2040 period. For each
 331 polymer, the heat source and recycling and residual waste treatment case combination with the lowest emissions in 2040 is shown. In
 332 all cases this was the case using heat generated from hydrogen produced by electrolysis. In the PBAT and PLA cases, the best end-of-life
 333 treatment method was 2.7% composting with 97.3% landfill; in all other cases 100% recycling and virtually indistinguishable from
 334 landfill.

335 In the UK, current common practice is for polymer manufacture using grid electricity and heat provided by gas, and recycling rates
 336 between 2.7% and 50% with residual waste treated by incineration. In this situation, the lowest current emission polymer in each pair
 337 is fossil-based PET in pair A, PLA in pair B, LDPE in pair C, and fossil-based HDPE in pair D, although a crossover occurs between 2.7%
 338 and 50% recycling rates, after which bio-based HDPE has lower emissions.

339 In this current situation, no polymers achieve lifetime emissions below zero. If residual waste is instead treated by landfill, bio-based
 340 HDPE is the only polymer able to achieve emissions below zero. Aside from bio-based HDPE (and by inference other PE grades), the
 341 only way to achieve emissions below zero is to use hydrogen generated by the electrolysis of water for heat production. With this heat
 342 source, bio-based PET, PLA and bio-based HDPE can all achieve emissions below zero, as Figure 9 shows.

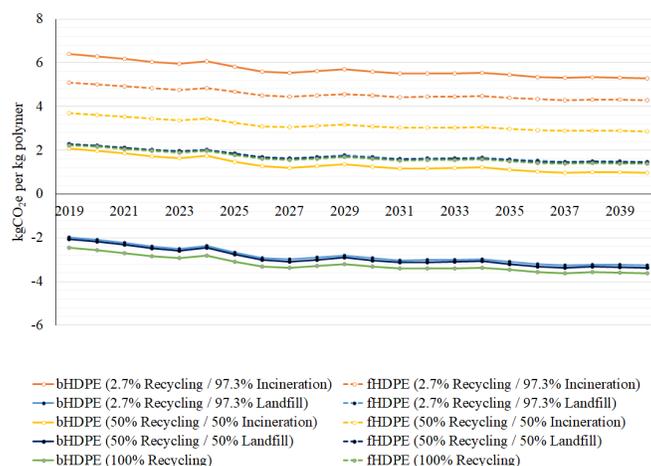


Fig. 8 Cradle-to-grave greenhouse gas emissions for fHDPE and bHDPE. Emissions per kg of final polymer with three recycling rates and two residual waste cases. Heat supplied by hydrogen from electrolysis in all cases.

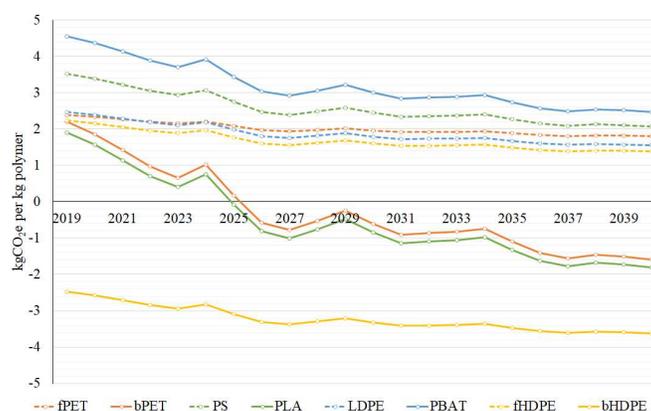


Fig. 9 Best case cradle-to-grave greenhouse gas emissions for eight polymers, showing the lowest emissions in each case. In all cases this is heat provided by electrolysis of hydrogen. End-of-life treatment by 100% recycling for fPET, bPET, PS, LDPE, fHDPE and bHDPE, and 2.7% composting with 97.3% landfill for PLA and PBAT).

344 4.2 Crossover points

345 Crossover points are defined as points in time after which a bio-based polymer may have lower lifetime emissions than a functionally
 346 comparable fossil-based polymer. Crossover points vary in time with heat source and end-of-life treatment method, but suggest when
 347 adopting bio-based polymers can help reduce overall emissions. Crossover points for comparison within pairs are summarised in Table
 348 4, with more detail given in the following section.

349 4.2.1 Pair 1: Fossil-based polyethylene terephthalate (fPET) and Bio-based polyethylene terephthalate (bPET)

350 If heat is provided by gas:

- 351 • With medium recycling rates and incineration, bPET has lower emissions than fPET from 2030.
- 352 • With low or medium recycling rates and landfill, or 100% recycling, bPET has lower emissions than fPET from 2025.

353 If heat is provided by Hydrogen from electrolysis:

- 354 • With low recycling rates and incineration, bPET has lower emissions than fPET from 2025.
- 355 • With medium recycling rates and incineration, bPET has lower emissions than fPET from 2021.
- 356 • With low or medium recycling rates and landfill, bPET has lower emissions than fPET from 2021.
- 357 • With 100% recycling rates, bPET has lower emissions than fPET from 2019.

358 4.2.2 Pair 2: Polystyrene (PS) and polylactic acid (PLA)

359 In all cases:

- 360 • Before 2021, 100% recycled PS has lower emissions than PLA with low recycling rate and incineration.
- 361 • After 2021, PLA has lower emissions than PS regardless of heat source or end-of-life treatment.

Table 4 Summary of crossover points from fossil-based to bio-based polymers within each polymer pair. Where a year is given, this is the first year in which the bio-based polymer has lower kgCO₂e/kg polymer emissions than the fossil-based polymer for the given heat source and end-of-life treatment method. Where 'None' is stated, the fossil-based polymer has lower emissions over the entire timeframe considered. Where 'Pre-2019' is stated, the bio-based polymer has lower emissions over the entire timeframe considered. Primary treatment methods are recycling for all polymers except PBAT and PLA, which are composted.

Waste treatment %	Residual waste treatment		Polymer pair (polymers)	Gas	Heat source	
	%	Method			H ₂ SMR	H ₂ electrolysis
2.7	97.3	Inc.	A (ffPET / bbPET)	None	None	2025
			B (PS / PLA)	Pre-2019	Pre-2019	Pre-2019
			C (LDPE / PBAT)	None	None	None
			D (fHDPE / bHDPE)	None	None	None
2.7	97.3	Land.	A	2026	None	2021
			B	Pre-2019	Pre-2019	Pre-2019
			C	None	None	None
			D	Pre-2019	Pre-2019	Pre-2019
50	50	Inc.	A	2031	None	2021
			B	Pre-2019	Pre-2019	Pre-2019
			C	None	None	None
			D	Pre-2019	Pre-2019	Pre-2019
50	50	Land.	A	2025	None	2021
			B	Pre-2019	Pre-2019	Pre-2019
			C	None	None	None
			D	Pre-2019	Pre-2019	Pre-2019
100	0	None	A	2025	None	Pre-2019
			B	Pre-2019	Pre-2019	Pre-2019
			C	None	None	None
			D	Pre-2019	Pre-2019	Pre-2019

362 **4.2.3 Pair 3: Low-density polyethylene (LDPE) and poly(butylene adipate-co-terephthalate) (PBAT)**

363 If heat is provided by gas:

- 364 • LDPE has lower emissions than PBAT unless LDPE is incinerated and PBAT is partially composted and partially sent to landfill, or
365 fully composted after 2031.

366 If heat is provided by Hydrogen from SMR:

- 367 • LDPE has lower emissions than PBAT unless LDPE is incinerated and PBAT is partially composted and partially sent to landfill.

368 If heat is provided by Hydrogen from electrolysis:

- 369 • LDPE has lower emissions than PBAT in all equivalent cases.
- 370 • After 2024, PBAT with a medium composting rate and landfill has lower emissions than LDPE with a low recycling rate and
371 incineration.
- 372 • After 2025, PBAT with a low composting rate and landfill has lower emissions than LDPE with medium recycling rate and
373 incineration.

374 **4.2.4 Pair 4: Fossil-based High-density polyethylene (fHDPE) and Bio-based High-density polyethylene (bHDPE)**

375 In all cases:

- 376 • With low recycling rates and incineration, fHDPE has lower emissions than bHDPE.
- 377 • In all other cases, bHDPE has lower emissions than fHDPE.

378 **4.3 Net zero polymers**

379 Recently, the potential to use bio-based polymers as a method of greenhouse gas sequestration has been postulated³³. For this idea to
380 work, polymers must have negative cumulative greenhouse gas emissions at the point of burial. The indicative Figure 2 shows a potential
381 pathway to this. Section 3 illustrates that with a combination of electricity defossilisation, heat source change and improvements in
382 end-of-life treatment, some bio-based polymers can have emissions below zero, so can theoretically sequester greenhouse gas. Of the
383 cases considered, fully bio-based PET, PLA, and bio-based HDPE are able to achieve this. All three are able to achieve net negative
384 emissions if heat is supplied by hydrogen generated from electrolysis. If heat is supplied by hydrogen generated by steam methane
385 reforming, or gas, only bio-based HDPE can be produced with net negative emissions.

386 100% recycling or composting rates are unlikely to be achievable in practice, but with 50% recycling rates and heat supplied by
387 hydrogen produced using electrolysis, bio-based HDPE can already be produced (if residual waste is sent to landfill and not incinerated),
388 and net negative bio-based PET can be achieved at emissions levels forecast for 2035. At 50% composting rates in the same heat case,
389 net negative PLA can be manufactured at emissions levels forecast for 2026 if residual waste is sent to landfill, or 2036 if incinerated.

390 Current grid emissions intensity is somewhat above that predicted by this projection however, meaning that the predicted dates
391 are sooner than can actually be achieved, but this still suggests that net negative emission bio-based polymers could be manufactured
392 within the next decade.

393 4.4 End-of-life treatment

394 End of life treatment has a significant impact on emissions, and on the time at which net negative emissions can be achieved. The
395 difference in impact between residual waste treatment by incineration or landfill can be observed in the difference in the time at which
396 net negative emissions are reached in the 50% recycling rate cases with residual waste treated by landfill or incineration. Typically,
397 residual waste treatment by incineration delays this time by 10 years relative to the date achievable with landfill.

398 Where polymers are suitable for composting (PLA and PBAT), this has been treated as the preferred end-of-life treatment rate.
399 However, total emissions are actually often higher in composting cases than the equivalent landfill case. This is due to the emission loss
400 from composting, as discussed in Section 2.4 and Table 2 and results in the lowest emissions cases for these polymers being those with
401 the highest landfill rates. Though true in greenhouse gas emission terms, composting may be preferable to landfill for other reasons.
402 The 55% value of C_{loss} may also vary with composting practices and systems, and this value is likely to reduce if composting was
403 undertaken at scale.

404 4.5 Sequestration

405 The potential to manufacture net negative polymers allows the concept of Neofossils³³ to be considered in detail. In this work it
406 was suggested that agricultural waste could be used to produce bio-based polymers, which after use could be buried to sequester the
407 remaining embodied CO₂. All cases in the present study have assumed the use of biological products from UK operations. Wheat straw
408 was used in the bHDPE case, wheat straw and forest residues were used in the bbPET case, and maize grain was used in the PLA case.
409 The study includes the growth of the maize and wheat straw products and the processing of the forest residue. The availability of
410 products and wastes is not the focus of this study.

411 In order to carry out the Neofossils proposal, polymers would require collection and curated burial. Collection has not been
412 considered in the present study. The energetics of curated burial would presumably be similar to that of current landfilling practices, so
413 the concept can be represented as a 100% landfill case. Current landfill practice data suggests that if heat was provided by hydrogen from
414 electrolysis, by 2030 bio-based PET, PLA and bio-based HDPE could be manufactured with emissions of the order of -0.19kgCO₂e/kg,
415 -0.85kgCO₂e/kg and -2.93kgCO₂e/kg polymer respectively.

416 More than 300 million tonnes of plastic are produced annually¹. Assuming this demand was met by an equal split between the three
417 polymers which achieve net negative emissions (i.e. 100 million tonnes each of bio-based PET, PLA and bio-based HDPE) suggests a
418 total potential for the capture of 397 million tonnes of greenhouse gas. If all 300 tonnes proposed was bio-based HDPE, total potential
419 capture would be 880 million tonnes of greenhouse gas, close to the gigatonne suggested³³.

420 5 Conclusions

421 Comparison of functionally similar pairs of fossil-based and bio-based polymers highlights that under certain combinations of heat
422 source and end-of-life treatment method, crossover points in time exist when bio-based polymers should be adopted instead of fossil-
423 based polymers. Three key crossover points have been identified:

- 424 • The crossover from fossil-based PET to bio-based PET is forecast to occur in 2030 based on a realistic UK scenario (heat provided
425 by gas and medium recycling and incineration rates).
- 426 • The crossover from polystyrene to PLA appears to have been passed, with PLA having lower emissions than polystyrene for all
427 heat source and treatment cases from 2021.
- 428 • Similarly, unless incineration rates are very high, bio-based HDPE appears to already have lower life cycle emissions than fossil-
429 based HDPE.

430 Some bio-based polymers are able to be produced with net lifetime emissions below zero under the correct combination of feedstock,
431 heat source and end-of-life treatment:

- 432 • Net negative fully bio-based PET using wheat straw and forest residues is forecast to be producible by 2026 using heat generated
433 from hydrogen produced by the electrolysis of water, if a 100% recycling rate is achieved, or 2035 with a 50% recycling rate.
- 434 • Net negative PLA based on maize is producible from 2030 using heat generated from hydrogen produced by the electrolysis of
435 water, if a 100% composting rate is achieved, 2026 or 2036 with a 50% composting rate and residual waste landfill or incineration
436 respectively, or 2025 with a 2.7% composting rate, provided residual waste is sent to landfill.

437 • Net negative bio-based HDPE from wheat straw is producible at current grid electricity emissions (according to BEIS projections),
438 and heat provided by gas, hydrogen from steam methane reforming, or hydrogen from the electrolysis of water, and at recycling
439 rates as low as 2.7%, provided residual waste is sent to landfill.

440 Using these polymers, negative emissions of between -0.19 and -2.93 kgCO₂/kg polymer can be achieved at electricity emissions
441 forecast for 2030, and between -0.85 and -3.26kgCO₂/kg polymer at electricity emissions forecast for 2040. It should be noted however
442 that these emissions rates may in fact be achieved in 2040 and 2050 respectively due to the lag between forecast and actual emissions
443 rates, this nonetheless highlights the potential bio-based polymers may provide as electricity supply defossilisation occurs.

444 Author contributions

445 **Stuart Walker:** Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing

446 **Rachael Rothman:** Conceptualization, Methodology, Writing - Review & Editing, Supervision

447 **Antony Ryan:** Conceptualization, Methodology, Writing - Review & Editing, Supervision

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