Industrial need for carbon in products

Final 25% Series Paper

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Katherine Collett, Mike Mason, Charlotte Williams,
Matthew Davidson, Brian O'Callaghan and Cameron Hepburn

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Final 25% series

The Final 25% project at the Oxford Smith School of Enterprise and the Environment aims to identify the landscape of key technological solutions for the final stages of the essential transition to net-zero, and then net-negative, CO_2 emissions.

The underlying premise is that 80% of emission reduction can be achieved by decarbonising electricity generation, transport and heating, and by improving energy efficiency, using technical solutions which are already the focus of significant research and development. The remaining 20% of global emissions are perceived to be difficult to decarbonise and currently lack clear reduction pathways. Research attention must be directed to these emissions sources now, so that necessary technologies and business models can be developed over time.

Net-zero emissions are unlikely to be enough to stabilise planetary temperature below a 1.5°C rise. It is likely that temperatures will overshoot; therefore, in order to limit climate change repercussions, there is a need to go net-negative, by absorbing between 2 and 20 Gt CO_2 per year by 2100 [1]. At the least, this is a further 5% reduction on top of eliminating present-day emissions.

The **Final 25% Series** focuses on the hard-to-abate sectors which form the final 20% of emissions, as well as ways of achieving 5% net-negative CO_2.

A key part of the project is a series of dinners convened in Oxford and London. The Oxford dinners, where selected guests include leading scientists, engineers and technologists, focus on the science and technology research and development needed to reduce emissions and achieve net-negative. The London dinners, where guests include leaders from finance, industry and government, explore how these new ideas can be funded and deployed at scale to make a material contribution.

This report series describes the conclusions of the discussions, offering recommendations based on the insights of experts working closest to these topics. The subjects covered in this ongoing series include nature-based CO_2 sinks, long-term energy storage, the future of cooling, alternatives to fossil carbon for industrial products and processes, bankable carbon capture and storage, and the climate impact of alternative proteins.

Executive summary

Fossil carbon-based products, including, but not limited to, materials such as polymers, asphalt, carbon fibre, pharmaceuticals, lubricants, solvents and fertilisers, are indispensable components of modern economic and social systems. One of the most significant and challenging product groups is polymers (plastics). Annual demand for polymers is close to 400 Megatons (Mt) [2], and demand is expected to rise at 4% pa to 2050 [3]. By 2050, it is estimated that 1.2 Gt of carbon per year will be needed to make these polymers. Traditionally, this carbon has been sourced from petrochemicals, accounting for 14% of oil and 8% of gas production [4]. However, in a net-zero greenhouse gas emissions (GHG) world this will create serious challenges.

Three approaches to sourcing carbon for polymer production in a net-zero carbon environment stand above the rest: (i) use of biomass (plants and wastes) as an alternative raw material, with atmospheric CO_2 uptake occurring during crop growth (ie indirect capture); (ii) use of CO_2 captured directly from the atmosphere or chemical processes as a carbon source; and (iii) circular use of waste or discarded polymer product as a source of carbon via recycling.

To meet the need for 1.2 Gt of carbon at least 4.5 Gt of CO_2 must be drawn down from the atmosphere, either mechanically or by growing biomass. This would be a very substantial addition to the 2 to 20 Gt CO_2 annual drawdown already needed for direct climate change mitigation [1]. Pursuing any one or a combination of these pathways will not be without significant challenge – additional multi-disciplinary research is essential to achieve the goal.

Until now, polymers have been manufactured to optimise for cost and function, with little consideration of product end-of-life. This has led to significant polymer contamination in our oceans and lands. If polymers do not decay or become safely buried by natural processes, they will simply accumulate *ad infinitum*. To prevent further increases in macro- and micro-polymer contamination, and increases in atmospheric CO_2, end-of-life considerations must also be prioritised. Avoiding endless accumulation means establishing a design paradigm for products which considers end-of-life options no matter how long the lifespans are.

Waste recovery and cycling carbon back into useful products will both reduce waste and also lessen demand for virgin feedstock. Increasing the value of wastes by requiring carbon to be sourced from sustainable sources could be a key tool to improving levels of waste recovery. Using waste will require closed-loop recycling techniques such as chemical recycling. This would allow polymers to be manufactured that are independent of the nature of the input waste feedstock. Increasing the value of waste in this way would help develop a market for polymer waste and attract private investment into waste recovery infrastructure.

However, it is impossible to guarantee recovery of all polymer waste. Thus, whilst all polymer products should be recoverable and amenable to recycling, they also need to be biodegradable – the exception being those polymers that can be shown to be compatible with the environment and pose no material risk even in substantial accumulations, described here as ‘eco-compatible’.

Whilst substitution with sustainable polymers is technically feasible, getting industry to switch and ensuring all the research is done in time will be substantial challenges. Research is urgently needed to develop both biodegradable and eco-compatible products to replace the suite of polymers currently in use, and to create techniques to recycle them efficiently and cost-effectively.

If fossil carbon is to be considered a feedstock for future polymers, research is needed to determine how the resulting polymers can be made biodegradable, how the resulting CO_2 can be captured (bearing in mind the priority to draw down substantial atmospheric CO_2 for climate change mitigation), and what the economics of a hydrocarbon industry might be like if it is only supplying the make-up carbon for polymers to account for losses in recycling.

It is essential that secure and properly targeted public funding is deployed to support nascent, early-stage research, and the subsequent transition through development to scalable and commercially viable products. It is unlikely that the necessary market growth or early-stage research can be conducted relying solely on private investment. Policy and support must focus not only on the production and end-of-life of products, but also on the sources of virgin feedstocks, be they from direct air capture or from novel crops and sources of biomass. Finally, clear regulation to enforce a portfolio standard of sustainable polymers is needed, together with a timescale for change, so that industry can manage the transition to sustainable polymers.

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1 Industrial uses of carbon

Global industry is responsible for almost 25% of greenhouse gas (GHG) emissions [5]. However, much of this comes from emissions associated with using fossil fuels for industrial energy (eg electricity, heating, drying and cooling). These energy-related emissions are not the subject of this report, the premise being that the world's future energy supply will be decarbonised. Instead, this report investigates the essential role of elemental carbon as a building block for making industrial products, such as polymers.

1.1 The role of carbon in industry

Industrially, carbon has two main uses: as a component in products and for its chemical reactivity. For the former, carbon is used in polymers, asphalt, carbon fibre, pharmaceuticals, lubricants, solvents and fertilisers. At the ultimate end-of-life of these carbon-rich products (possibly after several cycles through different products), disposal either leads to the release of the carbon into the atmosphere in the form of CO_2, or adds to landfill or ocean wastes. For the latter, carbon is used in industrial processes as a reducing agent for the production of materials including steel, aluminium and silicon. CO_2 is emitted during these processes. Many such processes can be modified to use hydrogen or ammonia as the reducing agent, in place of carbon. Carbon use for processes will be considered elsewhere in the Final 25% Series, in discussions about alternative reducing agents, such as hydrogen, and about research into CO_2-negative cement.

The focus of this report is on the use of carbon within products.

The most significant carbon-containing products by market volume are fertilisers, polymers (including plastics, elastomers and resins) and carbon fibre, as shown in Figure 1. This report concentrates on the largest and most rapidly growing group: carbon-containing products from oil, or polymers. In this report all references to polymers include plastics, elastomers, resins and related products and compounds. Zero-emissions production techniques for ammonia, which is used to produce fertilisers, are discussed separately within the Final 25% Series.

1.2 Where to source carbon for use in products?

Traditionally, carbon used in products has been sourced from the petrochemicals industry, which accounts for 14% of oil production, equivalent to 12 million barrels per day, and 8% of gas production [4]. The current flow paths from petrochemical source to carbon-containing products and secondary products are shown in Figure 1.

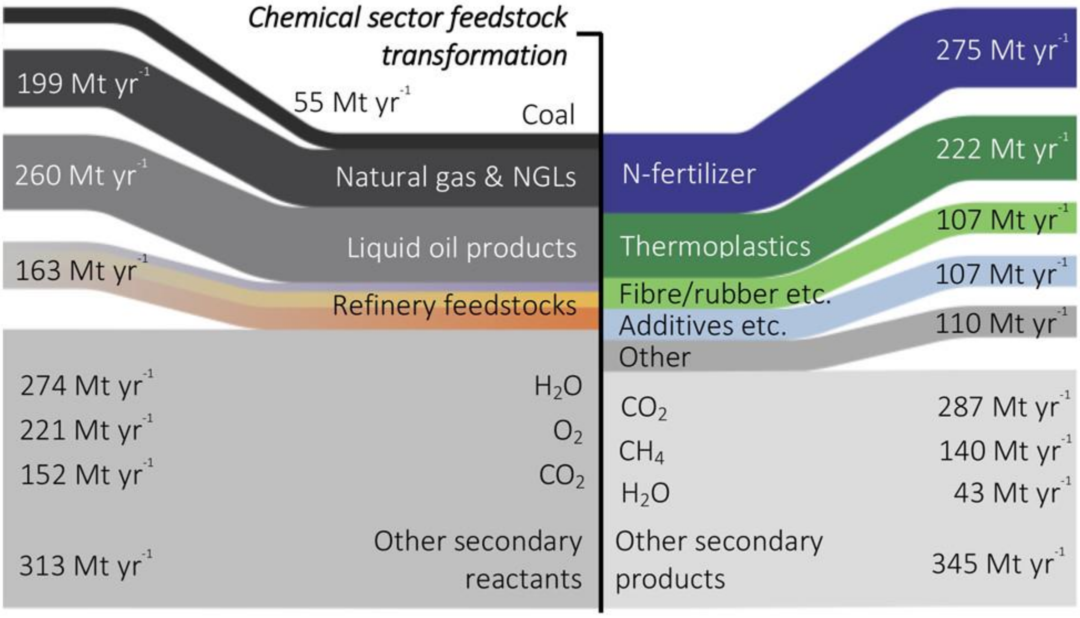

Figure 1 Global flow of chemicals from petrochemical industry to carbon-containing products and secondary products. Figure from Levi and Cullen [6]**.**

In a net-negative emissions world, the use of petrochemicals as the source of carbon may no longer be a viable option, for economic as well as environmental reasons [7]. Historically, petrochemicals have been a by-product, with refineries designed around meeting the demand for transport fuels [7]. If energy generation and transport are provided by non-fossil means the demand for fossil fuels as an energy source will disappear and the cost of pure 'oil-to-chemicals' processes is likely to increase. In addition, all fossil carbon extraction will also have to bear the economic burden of CO_2 capture and burial. Thus, it is likely that fossil carbon as a feedstock for polymer manufacture will become uneconomic compared to the alternatives.

As an alternative to virgin petrochemical carbon, sustainable sources of carbon can be found in biomass, atmospheric CO_2 or existing carbon-based products. These categories incorporate wastes, algae and co-products from industries using natural products (eg paper, farming, fibre products). Biomass as a feedstock for bio-refineries [8]–[11], can produce 'bioderived' carbon-containing base chemicals for products [12]. Atmospheric CO_2 can be used in conjunction with bioderived or petrochemical monomers to create polymers [9], [10], [13]. The use of existing carbon-based products is more commonly known as recycling and forms part of the circular economy.

One benefit of using biomass as feedstock is that this can sometimes (but not always) improve degradability and recyclability. Many of these novel polymers can be optimised to have properties comparable (if not superior) to those from produced from petrochemicals. The critical questions which remain are whether these polymers can be delivered at scale and at reasonable cost.

2 The end-of-life for carbon-containing products

Products have historically been manufactured to optimise for cost and function, with little consideration of end-of-life. This has led to significant polymer contamination in our oceans and lands [14]. Increasing global polymer contamination is such that, under a 'business as usual' approach, by 2050 the oceans will contain more polymer by weight than fish [15]. To prevent further increases in contamination and in atmospheric CO_2, the focus will need to shift towards end-of-life considerations [16]. Polymers and the products made from them must embrace flexible end-of-life options: recovery, recycling and degradation.

2.1 Recovery and recycling

Recovering products at their end-of-life is key to the goal of preventing polymer contamination of the environment. However, recovery is challenging and cannot be guaranteed. In 2015, at least 58% of global polymer waste was discarded or sent to landfill [3], although this figure varies drastically across regions. In the EU, 25% of *recovered* consumer polymer wasted ended up in landfill in 2018 [17]. Even when polymer waste is recovered, it is not always managed appropriately, resulting in much leaking into our rivers and oceans. Between 4.8 and 12.7 Mt of polymer waste from coastal countries reached our oceans in 2010 [18].

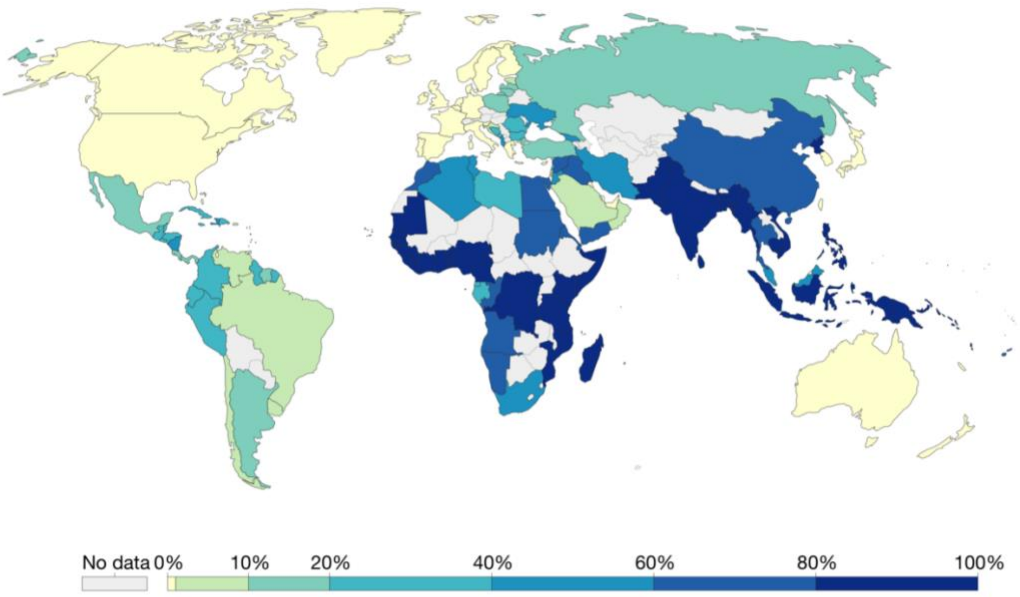

Figure 2 Share of plastic waste that is inadequately managed. Figure from Our World in Data [19]**. Data from Jambeck et al.** [18]**.**

Figure 2 shows the share of polymer waste that was inadequately managed globally in 2010. It is clear that whilst recovery and appropriate management of polymer waste cannot be guaranteed even in wealthy developed economies, it is especially challenging in Low- and Middle-Income Countries (LMICs).

Efforts to improve recovery are therefore valuable because recovery reduces environmental contamination and also allows recycling of the carbon contained in the products.

Recycling recovered polymer significantly reduces the need for virgin feedstock. Theoretically, recycling can create a closed-loop circular economy, so carbon stays within the system and does not escape into the environment as contamination. If some of the challenges associated with recycling are overcome (see below), the monetary value of polymer waste could increase because it would be a valuable carbon feedstock. This could provide an incentive to recover products and support the transition to a circular economy, reducing leakage of polymers into the natural environment [14].

Recycling currently faces significant challenges:

- It is energy-intensive. However, this energy can be sourced from renewable energy, negating any energy-related emissions, and is usually less than the energy required to produce the polymer from virgin petrochemicals [20].
- Mechanical recycling, currently the dominant form of recycling, degrades the quality of the polymer output due to contamination, unavoidable polymer mixing and thermal treatment [2]. Therefore, polymers cannot be mechanically recycled indefinitely [21]. Of all the polymer recycled in human history, only 10% has been recycled more than once [2]. Only 5% of the initial material value of packaging remains after recycling when all factors are considered (ie the small proportion which is recovered for recycling, the value losses in sorting, and reprocessing) [21]. Alternative recycling methods are discussed in Section 4.1.2 below.
- Product manufacturers seldom have commercial recycling incentives, so often their products are not designed for optimal recycling procedures [9]. This can mean that recycling is challenging, especially when a product comprises multiple materials. Incentives are needed to encourage product recovery and recycling at end-of-life (see Section 4.1.2). Mechanical recycling is only possible if recovered products can be separated into their constituent material components.
- Not all polymers are currently recyclable using mechanical methods, as discussed in Section 3.3.

Today, the annual recycling rate of polymers is estimated at a meagre 18% [3].

2.2 Biodegradable polymers

With few exceptions, it is impossible to guarantee 100% recovery of polymers. Thus, to avoid infinite accumulation, all polymers that are not 100% recovered must ultimately biodegrade.

Biodegradable polymers can be made from petrochemicals or bio-feedstocks. However, bioderived polymers are not necessarily biodegradable [12], [22]. In fact, at present, few polymers are both bioderived and biodegradable [12]. Figure 3 categorises polymers based on whether they are bioderived (ie bio-based) and/or biodegradable. At present, the global capacity to produce biodegradable polymers is only 4Mt [2], only 1% of the total annual polymer demand of around 400 Mt [2].

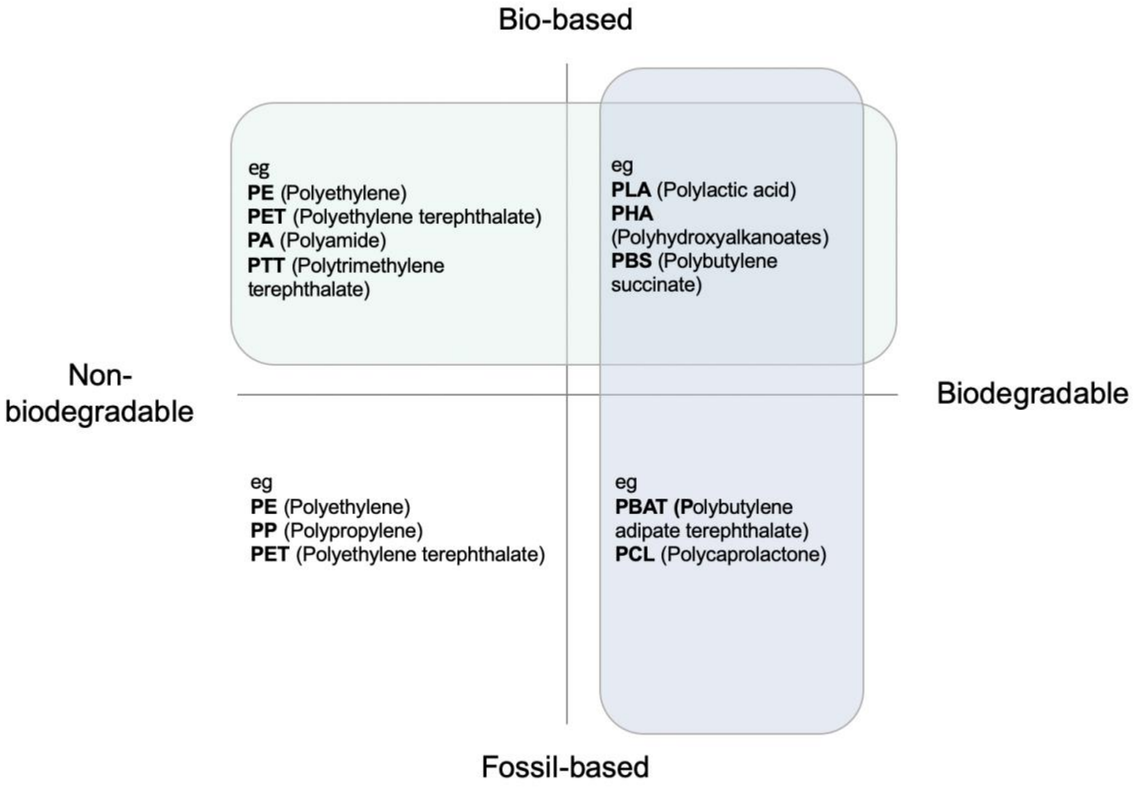

Figure 3 Matrix indicating universe of bio-based (bioderived) and biodegradable polymers. Adapted from International Energy Agency report on The future of petrochemicals, 2018 [4]**.**

Biodegradable polymers decompose ultimately to CO_2 and other harmless constituents by biological activity [23]. For some instances, where biodegradable polymers are not possible, an alternative would be to engineer products which might be deemed to be ‘eco-compatible’.

Eco-compatible products need to be safe in the environment, that is they should not fragment into particles that might find their way irretrievably into the food chain, nor decompose to or leach hazardous products, so that they ultimately find safe refuge by sinking and being buried in sediments.

Academic research into triggered degradation is gaining attention [9]. This would allow recoverable products with long-use lifetimes to degrade once triggered, either degrading into the atmosphere or breaking down into smaller molecules which could be recycled [9]. This will likely be a key future technology to provide products with sufficient function, but which can be re-formed, recycled or degraded according to preference and economics.

The challenges associated with biodegradable polymers are two-fold:

1. Biodegradable polymers decompose into CO_2, which is then released into the atmosphere. If derived from fossil sources this adds to the burden of direct air capture (DAC) where CO_2 is captured directly from the air. However, if produced from bioderived carbon the process of production and degradation remain in balance and no additional capture is needed.
2. Biodegradable polymers may only fully biodegrade under certain environmental conditions (ie a polymer designed to degrade in compost is unlikely to decompose in anything like the same timescale if it ends up in the ocean) [22]. Unless there is technological advancement in this area, high rates of recovery of these products is essential.

It is important to note that biodegradability and the ability to recover and recycle polymers are not alternatives. Unless leakage can be guaranteed not to happen, or the products are eco-compatible, all polymers should be designed to be both recyclable and biodegradable.

3 How much carbon is needed for polymers?

Annually, around 400 Mt of polymers are produced [2]. In order to analyse polymer demand for virgin carbon more thoroughly, we consider current recycling rates and polymer use-categories, and review which polymer types are recyclable, in order to understand what proportion of polymers could be recovered and recycled in the future and the potential need for virgin feedstock.

3.1 Current recycling rates

Between 1950 and 2015, only 9% of polymer waste was recycled [2], as shown in Figure 4. The vast majority has ended up in landfill or the natural environment.

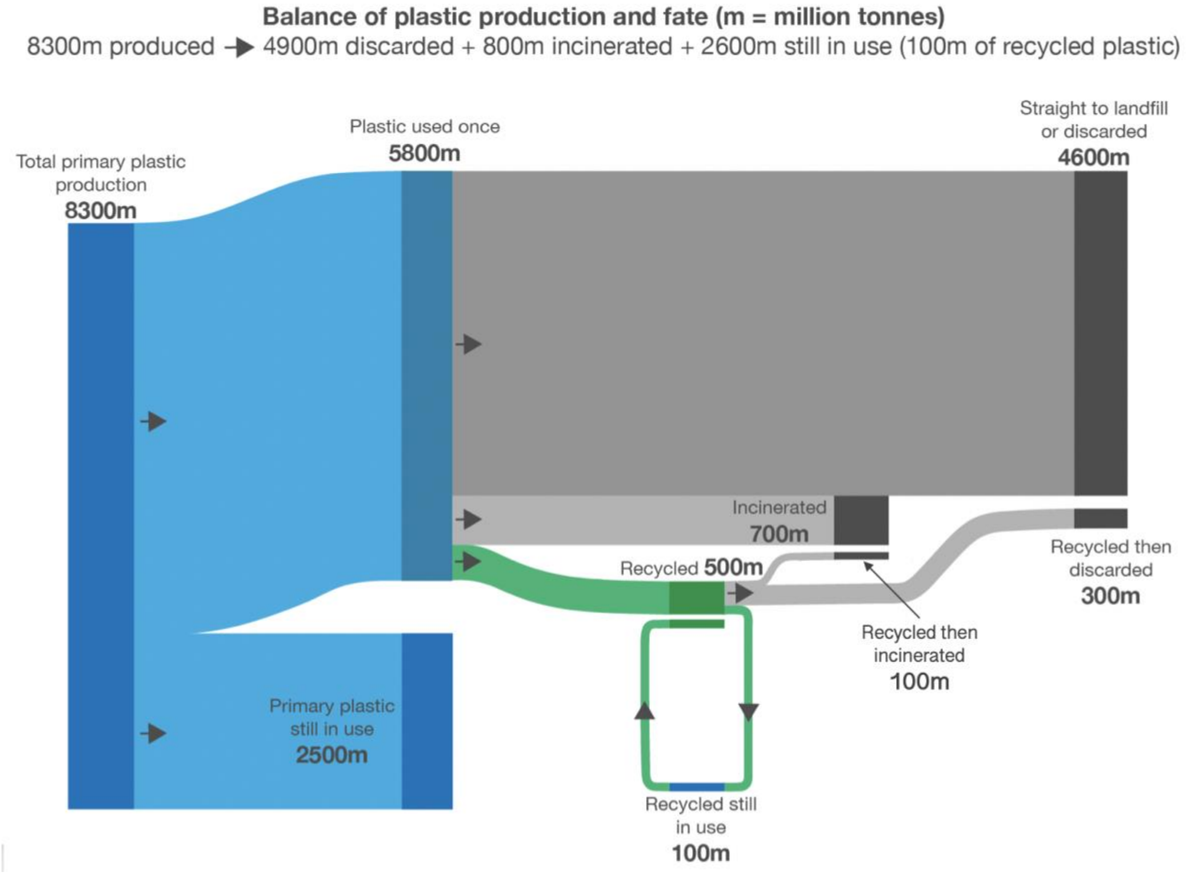

Figure 4 Fate of global plastic production 1950–2015. Figure from Our World in Data [19]**, using data from Geyer et al.** [2]**.**

In recent years, the recycling rate for polymer waste has been increasing. This increase is mainly due to efforts in High-Income Countries (HICs), where end-of-life recovery of products is greater. In the EU, recycling rates are higher due to incentives and landfill restrictions; recycling of post-consumer waste is between 30% to 40% [17]. However, recycling rates are significantly lower in LICs [15], where the future growth in demand for polymers will be located. At present, HICs consume up to 20 times more polymer per capita than in LICs [24]. It is vital, therefore, that polymer growth trajectories are incorporated into considerations of how to estimate future virgin carbon requirements.

Not all polymers are currently recyclable and not all recyclable polymers are currently recovered. Recovery depends heavily on the end-consumer, their access to recycling infrastructure, and the incentives they are given. A simple way to estimate recovery rates is to split the volume of polymer by use-categories.

3.2 Use-categories

Geyer et al. [2] identified eight use-categories for polymers: packaging, building and construction, textiles, consumer and institutional products, transportation, electrical/electronic, industrial machinery, and other. The 2015 annual demand for polymer by use-category is shown in Figure 5.

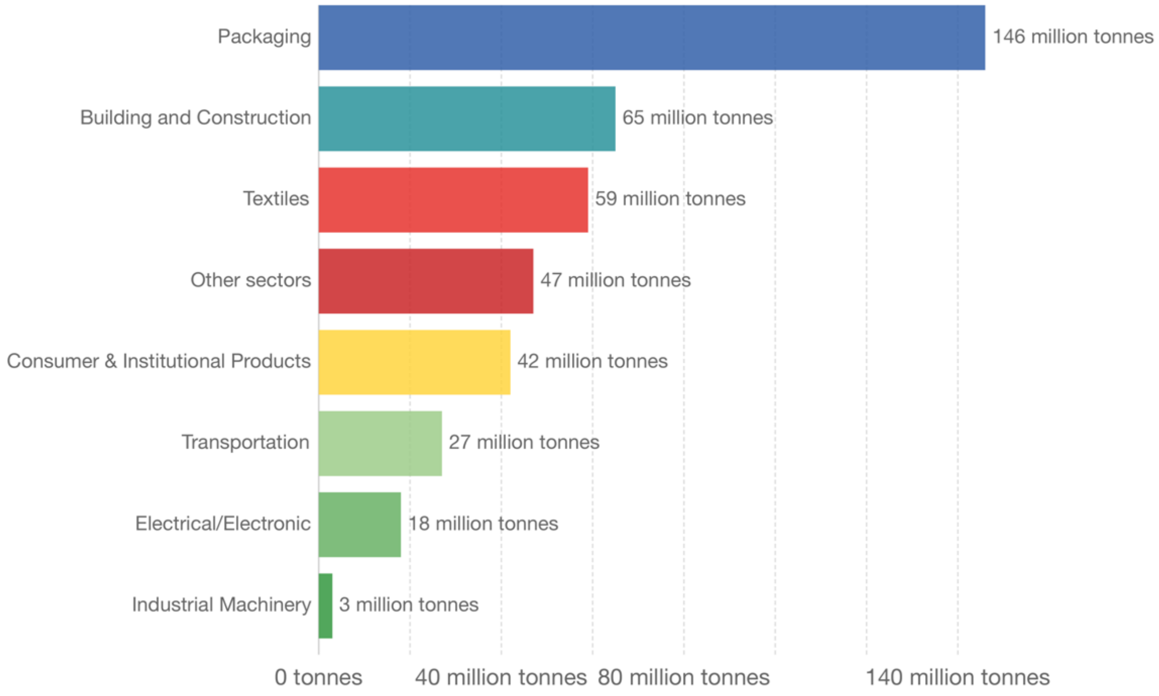

Figure 5 Primary polymer production in 2015 by use-category. Figure from Our World in Data [19]**. Data from Geyer et al.** [2]

These use-categories have three important, differentiating characteristics: the range of polymer chemistries they require, whether the materials can be recovered, and the time the product is in service (ie use-lifetime).

Table 1 shows the demand for polymer by use-category converted into the required carbon to produce the necessary polymers. The required carbon is calculated using the molecular weight of different polymer types whose demand distribution for each use-category is defined by Geyer et al. [2]. The % carbon by weight used for the different polymers is shown in the Appendix.

Table 1 Required carbon to satisfy polymer demand by use-category (2015 polymer distributions taken from Geyer at al. [2]**).**

Categorisation	2015 polymer demand (Mt)	2015 carbon required (Mt)	Relative demand by weight of carbon (%)
Potentially Recoverable	***113***	***75***	***25%***
Building and Construction	65	40	13%
Transportation	27	20	7%
Electrical/Electronic	18	13	4%
Industrial Machinery	3	2	1%
Recovery Challenging	***294***	***226***	***75%***
Packaging	146	116	39%
Textiles	59	42	14%
Other	47	34	11%
Consumer and Institutional Products	42	34	11%
Total	***407***	***301***	***100%***

In Table 1, the use-categories are separated into two classifications: ‘potentially recoverable’ and ‘recovery challenging’. The key characteristic of items which are challenging to recover (in the categories of packaging, textiles, other, and consumer and institutional products) is that they are manufactured in large quantities as consumer goods, meaning that their use is unmonitored and dispersed. Products which are challenging to recover account for 75% of the use of carbon in polymers. Although recovery of consumer goods may be possible in some countries, it cannot be depended upon. There will inevitably be some leakage in the system. Hence polymers must be designed to be biodegradable.

The items classified as recoverable are in the use-categories where finite numbers of products are produced and disposal could be monitored or made the responsibility of the manufacturer (building and construction, transportation, electrical/electronic, and industrial machinery). However, globally, this would require significant political will; there are considerable challenges associated with regulation and enforcement.

Table 1 shows that just over 300 Mt of carbon was needed in 2015 to manufacture all polymer products. Of the carbon used in products, 75% falls into the ‘recovery challenging’ classification. Even when polymers are recovered, not all are currently recyclable.

3.3 Which polymers are mechanically recyclable?

Due to current recycling methods, it is not effective to recycle all types of polymers. Be it for economic or technical reasons, only two main polymers are widely recycled; these are PET and HDPE [19], [25], used largely in bottles and plastic respectively. PET degrades very slowly. HDPE cannot be biodegradable and contributes to micro-polymers unless recovered. These two polymers make up around 20% of the global polymer market [2]. Since recovery is impossible to guarantee, to avoid environmental contamination, it may be that these polymers need to be replaced with alternatives.

Each use-category demands different volumes of different types of polymer. These have been used to calculate the proportion of recyclable polymer per use-category, shown in Table 2. In the analysis, the following (generous) assumptions are made [19], [25]: PET, HDPE, LDPE, PP, PUR and PP&A fibres are recyclable polymers [26]; and PVC, PS, Other and additives are non-recyclable polymers.

Table 2 Percentage of mechanically recyclable polymer by use-category.

Categorisation	Recyclable (%)	Non-recyclable (%)
Potentially Recoverable	***45%***	***55%***
Building and Construction	39%	61%
Transportation	61%	39%
Electrical/Electronic	36%	64%
Industrial Machinery	86%	14%
Recovery Challenging	***86%***	***14%***
Packaging	91%	9%
Textiles	100%	0%
Other	64%	36%
Consumer and Institutional Products	72%	28%
Total	***74%***	***26%***

From Table 2, 74% of polymers could be classed as mechanically recyclable. However, this may be optimistic. Some of the theoretically recyclable polymers are complexly integrated with other polymers which are not recyclable – separation of mixtures can be a problem, especially for mechanical recycling.

Many suppliers have or are considering alternatives to polymers, such as paper and cardboard. These must be produced from forests or biomass sources that are in sustainable rotations so that their use does not result in net CO_2 emissions. However, difficulties arise when paper and card are polymer-coated. This coating can be important, for example, if any water contact is anticipated, but introducing unrecyclable polymers in the coatings will result in leakage to the environment and formation of micro-polymers. Such coatings must therefore be biodegradable. The biodiversity impacts from growth of crops for manufacturing the paper and cardboard must also be considered.

It is evident from Table 2 that recyclable polymers make up the majority of the ‘recovery challenging’ categories, accounting for 86% of carbon use. This illustrates that a vast volume of polymer with the potential to be recycled may not be recovered and thus may never reach a recycling facility. In fact, between $80–120 billion in plastic packaging material is lost from the global economy each year after just one use [15].

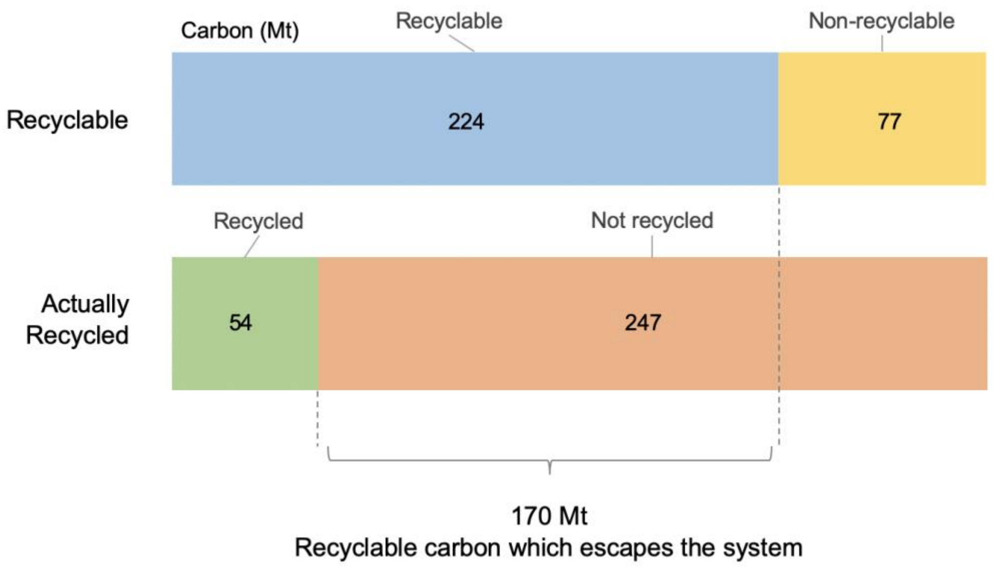

Figure 6 Mass of carbon in polymers which is mechanically recyclable compared to what is actually recycled each year.

The top bar in Figure 6 shows, using the classifications made in Table 2, that 224 Mt of the carbon in polymers should be recyclable. However, based on the global average recycling rate of 18%, the lower bar in Figure 6 indicates that only 54 Mt of this carbon is actually recycled. This means that 170 Mt of the 224 Mt of recyclable carbon is not currently recycled; 76% of the recyclable polymer is discarded.

3.4 How much carbon is needed now and, how much will be needed in 2050?

In 2019, using the current recycling rate of 18%, 54 Mt of carbon would have been recycled (Figure 6), meaning that the remaining demand needed to be met by virgin carbon. By 2050, some forecasts show that demand for polymers could have increased under a ‘business as usual’ scenario by up to 400% [3], [4], [15], which is a compound annual growth rate of 4% from 2015 [3]. Assuming polymers were demanded at the same ratios, this increase would result in a demand for over 1.6 Gt of polymer by 2050, requiring 1.2 Gt of carbon. If recycling rates were to remain unchanged, only 0.2 Gt of carbon would be recycled, leaving a minimum annual demand for carbon to manufacture products of 1 Gt.

As a worst case, if all of the 1.2 Gt of carbon was sourced from bio-feedstocks, this would require almost 4.5 Gt of CO_2 to be absorbed from the atmosphere by those plants (calculation in grey box). This is a significant additional need, on top of the climate mitigation requirement to sink 2 to 20 Gt CO_2 per year by 2100 [1], as discussed in another report of the Final 25% Series, *Nature-based sinks for CO_2 and sources of carbon feedstocks* [27]. Improving recycling rates is key to reducing this annual demand for virgin carbon.

For 1 Gt of carbon, 3.7 Gt of CO_2 needs to be drawn down

Due to the difference in molecular mass, for every 1 Gt of carbon atoms, 3.7 Gt of CO_2 is needed. This is the best-case scenario; there will inevitably be losses in conversion from CO_2 to useful carbon.

4 Recommendations for action

There is a pressing need to transition to zero-emissions polymers, whilst at the same time avoiding additional polymer contamination of the natural environment. Micro-polymers in oceans are a particular cause for concern. This transition will require the scaling up of global waste recovery, improved recycling rates and the near-complete replacement of current polymers with biodegradable equivalents made from non-fossil carbon sources. Promising technical solutions exist; however, they suffer from a lack of funding and often struggle to scale due to higher costs than petro-carbon and resistance from petrochemical incumbents. Therefore, regulation and policy will be of the utmost importance in facilitating this transition.

At the international Chemical Sciences and Society Summit in 2019, four key research challenges were highlighted: understanding the environmental impact of polymer waste; designing new, more sustainable polymers for future use; developing technologies that help with recyclability and/or degradation; and moving to closed-loop recycling [9]. The recommendations for action in this report build upon the latter three, considering both technical research and policy needs.

4.1 Priority areas for research and development

To achieve sustainable zero-emissions carbon for use in products, research and development (R&D) is needed in two main areas: biodegradable polymers made from non-fossil carbon (developing biodegradable polymers, and identifying suitable feedstocks), and advances in technologies to improve recyclability.

4.1.1 Biodegradable polymers made from non-fossil carbon

There are two areas of research that are needed to enable affordable, property-comparable, sustainable polymers: (i) biodegradable polymers made from biomass or CO_2 need to be developed, with properties comparable to their petrochemical-derived non-biodegradable equivalents, and (ii) suitable bio-feedstocks must be identified.

4.1.1.1 Developing biodegradable polymers from non-fossil carbon

As discussed in Section 3.2, perfect recovery of products is not possible; at least 75% of all carbon in polymers is challenging to recover. To prevent polymer pollution, polymers must be designed to be biodegradable. Efforts to improve recovery are essential, but it cannot substitute for biodegradability when there is unavoidable leakage. These biodegradable polymers must be made from non-fossil carbon, so that on a lifecycle basis they will not increase concentrations of CO_2 in the atmosphere as they degrade.

At present, the number of polymers which are both bioderived and biodegradable is limited, as shown in 2.2. Furthermore, biodegradable polymers generally only decompose fully when exposed to particular environments [22]. Research is needed to expand the range of these polymers, and improve the highly complex degradation mechanisms at end-of-life while maintaining product properties during use-lifetime. This must be accompanied by analysis to assess their effects on the environment [9], [22].

The main challenge with using sustainable carbon sources is that not all polymers currently in use can be manufactured with the same properties as petrochemical polymers. This diversification of the property and performance palette of sustainably derived polymers is an essential area for future research. Experts are confident that bioderived polymers will be able to be produced with a more diverse range of properties compared to those typical in petro-derived polymers [8].

At present, challenges present themselves in the form of property characteristics such as sensitivity to hydrolysis, degradation induced by processing at high temperatures, poor mechanical and barrier properties, and unsuitable glass transition temperatures [8]. These characteristics need to be resolved to allow bioderived polymers to compete commercially.

4.1.1.2 Identifying suitable alternative feedstocks

Alternative feedstocks include biomass and atmospheric CO_2.

The crops grown for bio-feedstocks must avoid competition with food crops; this is widely considered in the literature. However, there may be additional crops which have been overlooked until now. Crops that grow in agriculturally unfavourable areas could be of particular interest. In the accompanying report *Nature-based sinks for CO_2 and sources of carbon feedstocks* [27], the use of Crassulacean Acid Metabolism (CAM) plants (which grow in semi-arid land), halophytes (which can cope with high salinity) and algae are discussed. Certain varieties of these species have been reported to provide a valuable source of bio-carbon, in the form of platform chemicals [28], [29] [30], [31], and complex hydrocarbons [32], [33]. However, only a small number of the over 16,000 CAM species [34] and 1,500 halophyte species [35] have been investigated. Algae has also been identified as a promising feedstock. Research is needed into these plants to evaluate which are most suitable for low cost bio-carbon production.

Atmospheric CO_2 can be used in conjunction with bioderived or petrochemical monomers to create polymers [9], [10], [13], with 30–50% of the polymer mass being derived from CO_2 [12]. Atmospheric CO_2 can be gathered through Bioenergy with Carbon Capture and Storage (BECCS) or DAC. The advantage of this is that polymers created using non-fossil carbon can be classified as Carbon Capture and Utilisation (CCU), which is especially beneficial when used for products with long use-lifetimes [36], [37].

4.1.2 Advances in technologies which improve recyclability

Recycling reduces the annual need for virgin feedstock, which will be of great importance as we transition to zero-emissions polymers. One central challenge with present-day recycling is that the vast majority is mechanical (sorting, stirring and melting of polymers). This process is relatively cheap and scalable [38]; however, it is vulnerable to contamination and degrades the polymer's mechanical properties [15], [39], [40], making it suitable for only some grades of pure PET and HDPE [20]. Instead, we need a flexible recycling system.

The main alternative is chemical recycling [38], [39] (which can use biocatalysts [40]). In chemical recycling, no sorting is necessary; the waste material is broken down into smaller carbon-containing blocks, which can then be re-built into polymers. The advantage of this is that the properties are unaffected, offering the potential of a truly circular economy [20]. Although chemical recycling is conducted commercially (eg by Recycling Technologies [41] and Plastic Energy [42], [43]), it is expensive due to current energy costs [20], but these should drop with falling prices in renewable energy and improving process efficiencies. Recently, enzymes able to break 90% of PET into monomers within 10 hours have been reported in *Nature* [40]. Further research into alternative mechanisms is necessary in moving towards a closed-loop circular economy for polymers, especially concerning polymers which are not suitable for mechanical recycling.

4.2 Policy

Policy and regulation will play major roles in increasing the global recovery and recycling rates of waste products, and in supporting early-stage investment in R&D of sustainable alternatives to fossil carbon.

4.2.1 Support of R&D into biodegradable polymers and alternative feedstocks

Funding for R&D into biodegradable polymers will need to come from the public purse because avoiding polymer pollution and mitigating climate change (given that the polymers use sustainable feedstocks) are common goods.

Use of non-fossil carbon as feedstock will result in the evolution of a private market because the carbon is used to create polymers of value. Improvement in techniques to use non-fossil carbon will further lead to economies of scale, making private investments into the industry more attractive. However, in their early stages, these technologies face a challenge. Fossil-based polymers (and other products) are extremely cheap because the petrochemicals are a by-product of fossil-fuel extraction. Non-fossil carbon struggles to compete with the oil and gas incumbents on feedstock cost [8].

Early-stage R&D into non-fossil carbon, facing high costs with low benefits, will require public investment. Encouraging joint public–private investment in research, development and scaling of non-fossil carbon feedstocks could provide value for taxpayer money. Policy and regulation could be used to encourage private sector investment in the use of non-fossil carbon while deterring the use of fossil carbon (for example, regulation to enforce a portfolio standard). The benefits of diversity of supply chains and localised manufacturing should be emphasised.

4.2.2 Incentives to encourage global recovery and recycling at product end-of-life

Although products will need to be designed to be biodegradable, efforts to increase recovery and recycling help build a circular economy and reduce need for virgin feedstock. As demonstrated in Figure 6, two thirds of recyclable polymers are not recycled under current regimes, with waste recovery success varying substantially across the globe.

Policy to incentivise the use of non-virgin petrochemical polymers and any novel polymers will likely be necessary to help give these materials added value and improve recovery and recycling.

To increase recovery, the Royal Society report on microplastics [14] acknowledges that ‘regulation, incentives, penalties, voluntary agreements and new solutions’ will be necessary. Effective solutions for increasing recovery may be challenging in some LMIC regions due to lack of capital. To prevent this problem being exacerbated, limits should be placed on the export of polymer waste from HICs to LMICs for disposal.

One promising pathway to increasing rate of recovery is through increasing the value associated with polymer waste. There is a strong link between chemical recycling and the incentive to recover waste. Commercial profitability of recycling mechanisms which do not impugn the material properties of recycled materials, such as chemical recycling, would create a market for polymer waste. The increased market value of waste polymer as a viable alternative to virgin carbon could attract large commercial companies to invest in waste recovery infrastructure, especially in LMICs where governments are unable to do this themselves.

To complement this, ‘design for recycling’ is a key concept that must be promoted to facilitate a transition to a circular economy. Policy and regulation to encourage design for recycling could lead to reduced sorting requirements and easier separation of products’ constituent materials [39].

For larger items, it may be reasonable to place responsibility for product disposal, and thus the cost associated, on the manufacturer, creating an incentive to optimise product design for recycling. This could be implemented through Extended Producer Responsibility laws, which place the liability of product disposal on the producer (as is the case with electric vehicle batteries) [39].

4.2.3 Enforcing a portfolio standard

Introducing regulation of a portfolio standard could facilitate the transition to sustainable polymers. Legislating that corporations must include biodegradable polymers manufactured using sustainable feedstocks encourages industry engagement. Planned regulation must be published with a timescale for change, so that industry can manage the transition to sustainable polymers.

5 Conclusions

In 2050, in a net-zero emission world, the petrochemicals industry will no longer exist as we know it. By 2050, over 1.2 Gt of carbon will be used each year as a building block in manufacturing products, for example in polymers. This carbon will need to be sourced from non-fossil feedstocks. The dominant sources of this carbon are likely to be (i) bio-feedstocks, which absorb atmospheric CO_2 through photosynthesis during growth and can therefore be zero-emission; (ii) atmospheric CO_2 captured directly from the atmosphere or as a product of BECCS, which allows polymers to be produced; and (iii) existing carbon-based products. Due to the difference in molecular weight, producing 1.2 Gt of carbon would require at least 4.5 Gt of CO_2 to be drawn down from the atmosphere (either via photosynthesis, or directly). This is in addition to the 2 to 20 Gt CO_2 drawdown needed for climate change mitigation.

Polymers meet one of two fates: they become waste (which, if incorrectly managed, can result in micro-polymers) or CO_2 (after decomposition). The time before a product reaches either of these fates can be extended by recovery and recycling. However, recovery is not perfect; there will inevitably be leakage in the system. Any waste that is not recovered must biodegrade to prevent the continued environmental damage being caused by polymer pollution.

Improving recycling rates has the advantage of reducing the demand for virgin feedstock. To improve recycling rates, which are currently only 18% globally, initiatives are needed to assist infrastructure development (through both public and private financing) and to limit export of polymer waste from HICs to LMICs. The success of closed-loop chemical recycling would increase both the applicability of recycling and the value of waste polymer. This could result in the natural evolution of a private market for polymer waste. Public funding of chemical recycling techniques, therefore, has dual value.

Zero-emission polymers will require non-fossil feedstocks derived from a combination of bio-feedstocks and atmospheric CO_2 to top up losses from unrecycled products and to allow for market expansion.

Two priority research areas are highlighted. Firstly, research is needed into biodegradable polymers made from sustainable non-fossil carbon feedstocks. This should focus on improving material properties and identifying suitable feedstocks. Secondly, technologies to improve recyclability require attention. Most importantly, advances in chemical recycling are necessary to improve recovery and recyclability of all polymers.

Policy is needed to support three key areas. Firstly, early-stage R&D into biodegradable and bioderived polymers is unlikely to receive sufficient private investment. For bioderived polymers, advances will be accelerated with support from the public purse until the business case is scalable and competitive. Secondly, policy and regulation to incentivise recovery and recycling will be useful in reducing demand for virgin feedstock. Thirdly, portfolio standards should be introduced, which would require industry to include sustainable polymers as part of their products. These standards could increase with time, thus assisting industry with the transition to sustainable polymers.

Appendix

Polymer	Carbon by weight (%)
LDPE, LLDPE	85.6
HDPE	85.6
PP	85.6
PS	92.3
PVC	38.4
PET	62.5
PUR	59.1
Other	72.7
PP&A	71.5

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