Getting it right from the start
Developing a circular economy for novel materials

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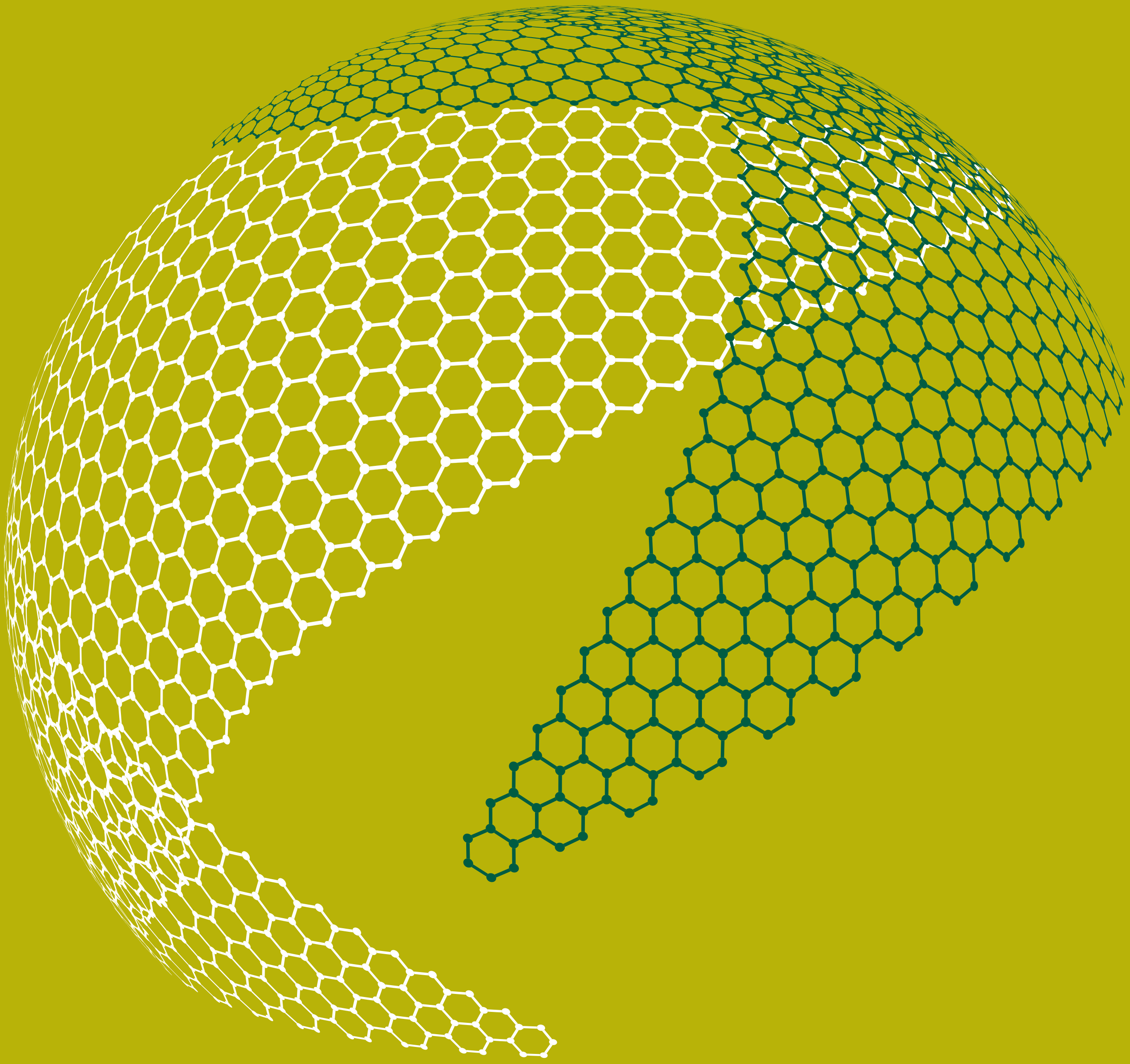

Getting it right from the start
Developing a circular economy for novel materials

By Jonny Hazell

The views expressed in this report are Green Alliance's own.

Green Alliance
Green Alliance is a charity and independent think tank focused on ambitious leadership for the environment. We have a track record of over 35 years, working with the most influential leaders from the NGO, business, and political communities. Our work generates new thinking and dialogue, and has increased political action and support for environmental solutions in the UK.

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Foreword

There are many definitions of the circular economy but all share a common core: to keep resources in productive use for longer. At Innovate UK we support a wide range of projects that are not only developing novel materials and manufacturing capabilities, but also the new components and products made with them. Further value can be added to these innovations through circular economy approaches which recognise the intrinsic worth of a material and seek to maximise the preservation of that worth, from product life extension through to recycling.

The work we have done with Green Alliance has developed a general framework for assessing the circular economy potential of novel materials, exploring three examples in detail. In each case opportunities for further innovation have been identified. I hope this report will act as a catalyst for future research, development and growth in this area.

Simon Edmonds
Director, manufacturing and materials, Innovate UK

Summary

With the right strategy and incentives, the ability for novel materials to be reused, recovered and recycled can be designed in at the outset.

Novel materials go hand in hand with improving technologies. Carbon fibre enables lighter weight, more fuel efficient vehicles; bioplastics promise to be superior to fossil fuel derived plastics; and additive manufacturing will be at the heart of the next generation of industry.

But these new materials and techniques have a sting in the tail: they can make it harder to recover value from products that have been thrown away. Just as we are developing a circular economy, where more and more waste is converted back into useful raw materials, these novel materials risk disrupting the system and creating a new generation of products destined for landfill.

This isn't a foregone conclusion. With the right strategy and incentives, the ability for novel materials to be reused, recovered and recycled can be designed in at the outset. The business models that make it possible to recover value from discarded products, can help to inform this design process.

In this report, we examine three examples of novel materials or techniques: carbon fibre composites, bioplastics and additive manufacturing, and show how they currently present both challenges and opportunities for a more circular economy.

We set out how challenges might be met and opportunities realised, through a combination of public and private sector action. These span research and development, funding for scaling up and the development of new supply chains.

In working through these examples we illustrate the thought processes needed for a good fit between material innovation and the circular economy. For this to happen it is necessary to think ahead and the methodology set out in this report should help that process.

We also demonstrate the clear need for collaboration across the supply chain: designers and manufacturers talking to end of life processors; manufacturers and end of life processors developing markets for recovered products; and consumers aware of and engaged in the right collection options.

The UK boasts leading innovation institutions and a very welcome public funding commitment to more competitive, dynamic manufacturing. Central to the success of this strategy will be innovation that increases resource productivity, ensuring that effective recovery is designed into all novel materials and that new technologies produce goods fit for a circular economy. This would prevent new materials burdening a resource supply system already struggling to keep within sustainable limits. And it would provide manufacturers with new sources of materials from more diverse, UK-based supply chains.

Introduction

Humanity's success in material science is written into our history. Our early progression, from the Stone Age through the Bronze Age to the Iron Age, demonstrates the relentless development of novel materials: stronger, lighter or more versatile than those that came before. But such has been our success that we are long past an age that could be summed up by a single element. The range of materials used by industry has become ever more complex, not just in terms of their variety, but also in their scale and how they are used together.

The development of many novel materials has led to improved environmental outcomes, such as lighter materials that enable more fuel efficient transport. But there are downsides too, as increased complexity makes it harder to recover value from products when they are thrown away.

Resource recovery systems have evolved to handle materials that have been used at a large scale for years. This has made it possible to keep valuable products or materials out of landfill and process them for resale.

But novel materials may have qualities that require new waste management infrastructure: first to identify and separate them, and then to reuse, remanufacture or recycle them. Unless they can be dealt with effectively in the waste stream, novel materials will be discarded as residual waste at best or will contaminate existing value recovery systems at worst. Given the growing concerns about environmental impacts and resource limits, this is environmentally and economically unsustainable.

However, if these factors are considered early enough in the development of a new material, potential problems can be avoided. Ways to capture economic and environmental value for future use can be designed in from the start. And, by increasing resource productivity, this approach will be important to improving the international competitiveness of UK manufacturers.

With the support of Innovate UK, the Engineering and Physical Sciences Research Council (EPSRC) and the High Value Manufacturing (HVM) Catapult, we have developed a methodology, outlined in this report, to assess the resource productivity of three example novel materials and processes: carbon fibre reinforced polymers, bioplastics and the materials and technologies used for additive manufacturing. We have considered what happens to them at the end of their life, and the capacity for resource recovery systems to process them.

Our findings will help material developers, users and end of life processors to identify where opportunities are being missed and what changes to products, technologies or systems are required to realise them.

What are novel materials?

Novel materials are those materials that are in some way new to the industrial system. Recent examples include nanoparticles, graphene and the rare earth elements, such as neodymium and dysprosium. Whilst nanoparticles and graphene are relatively recent discoveries, the first rare earth elements were identified at the beginning of the 19th century, demonstrating that what matters in the context of novel materials is not their existence but their entry into the industrial system at commercial scale.

These examples also highlight another distinction of novel materials which is that the elements involved can be familiar, but when arranged in a new way they can have significantly different functionality. For example graphene is made from carbon, whilst nanoparticles of silver have anti-microbial properties that make them useful for medicine.

One rapidly emerging source of novelty is materials based on combinations of other materials, referred to as composites. Many of these incorporate widely established materials, such as paper, plastic and aluminium, but their combination either enables the same functionality at lower cost than using them individually, or a different functionality that none of them could achieve alone.

What we mean by a circular economy

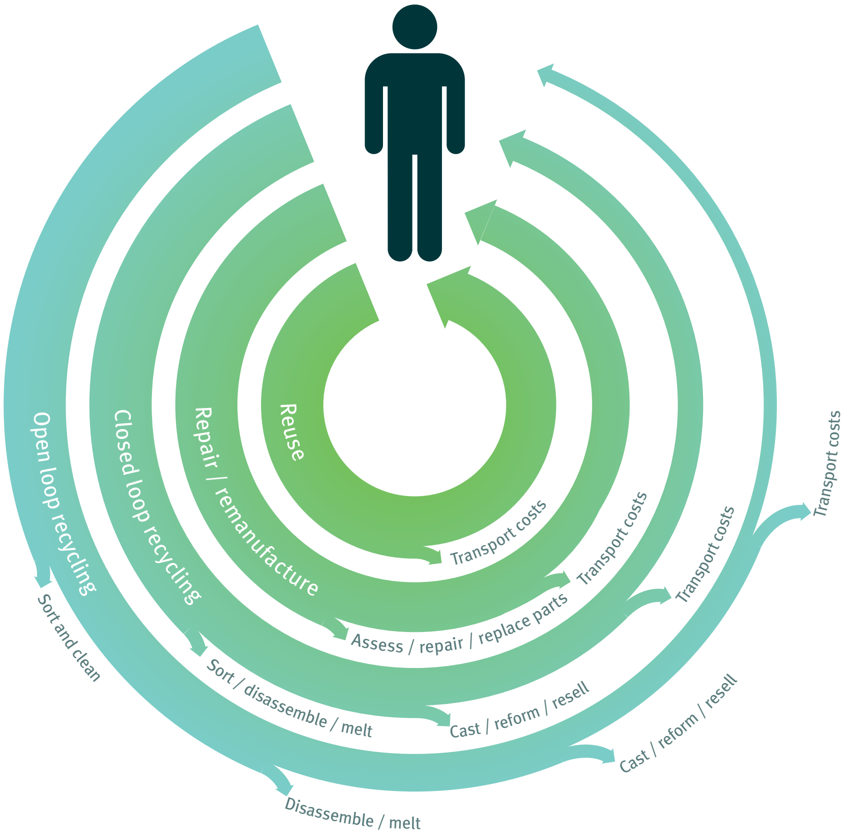
A circular economy is one that keeps materials in use, at their highest value, for as long as possible. It does so through products designed to be long lasting, easy to repair and recycle, and through systems that capture those products when they are no longer wanted, either to sell them on to another user or recover their materials for another use.

Reuse is the most economically and environmentally beneficial strategy within a circular economy. Finished products are worth much more than the raw materials they are composed of and direct reuse preserves the most value and embodied energy. For example, a reused iPhone retains around 48 per cent of its original value after two years, whereas the value of the materials you can recover from it is just 0.24 per cent of its original value.

If a discarded product is not immediately suitable for resale, sometimes it can be restored to a sellable condition through repair, refurbishment and remanufacturing. Remanufacturing is especially prevalent in the automotive sector and analysis suggests it saves at least 70 per cent of the materials required to make new goods.[1]

Where a product cannot be resold, closed loop recycling is the next best opportunity to recover some of its value. This involves using waste to make new products without changing the inherent properties of the material being recycled. Examples include bottle to bottle or alloy to alloy recycling. This includes recycling where the product changes

“What matters in the context of novel materials is not their existence but their entry into the industrial system at commercial scale.”



but the quality of the material is maintained, eg a plastic bottle made of polyethylene terephthalate (PET) which is recovered and used to make a toy.

The way waste products are collected and sorted can mean it is not always possible to reprocess a material to its original quality because there is too great a mixture of qualities and additives to process together. Under such conditions, the only opportunity to capture value is open loop recycling, otherwise known as downcycling. This uses recovered materials in place of lower value materials; for example glass, originally used for packaging at £50 per tonne, is crushed and reused as construction aggregate with a maximum value of £15 per tonne.

Systems needed for a circular economy

The process a product goes through at the end of its life, and how much of its original value is recovered, is determined by a series of interrelated factors, set out in the table below.[2] Some of these factors are inherent to the material, others to the product they are used in. To identify the likely outcomes, a series of questions should be asked about a material in the context of the particular product and the recovery systems in place. By ‘end of life’, we mean a product that has been used and discarded by its last user. Production processes also create wastes and, as the table demonstrates, many factors can increase the likelihood of recovering value from these. In particular, process wastes are more likely to be the responsibility of a single owner and arise in relatively pure and concentrated forms.

In this report we focus on materials and processes involved in the context of products used at the mass market scale and how to make the most of them.

Characteristic	Circular use likely	←----→	Circular use unlikely
Value Products or materials with high value or high end of life harm justify investment in recovery.	High	Medium	Low
Control, collection and communication The ability to control or reliably collect a known quantity of materials or products enables circular models.	Single owner	Two owners	Many owners
Ease of recycling, remaking and reusing Circular systems are more likely where the physical characteristics of products or materials make them easy to transform.	Easy	Moderate	Difficult
Pace of change If a product or material’s function changes too rapidly, investment in recovery may not occur. This is especially an issue where material substitution, technological development or fashion alters demand rapidly.	Slow	Medium	Fast
Concentration and contamination Where materials are dissipated or contaminated, recovery is either more expensive or impossible.	Pure and concentrated	Moderate	Contaminated and dispersed

There are three processes involved:

Collection

The necessary first step to recovering the value of any waste product or material is to retrieve it in a condition that enables reuse or recycling, a process often referred to as reverse logistics. These can take a wide variety of formats, eg using the postal service to return old mobile phones to refurbishers and resellers, delivery lorries that backhaul packaging from retailers for recycling, and the public and private recycling collections provided by resource management companies.

These systems can be entirely commercially driven based on the inherent value of the product, such as scrap metal collections. The economics are helped by market mechanisms, like landfill taxes, that increase the cost of alternative disposal routes.

The collection of other products will be driven by legislative requirements such as those for household packaging, waste electricals and electronics, portable batteries and end of life vehicles.

Sorting

Once a product is collected, value recovery depends on the availability of infrastructure to convert it into a resellable product or material. This is typically a two stage process. The first stage separates any products, parts or components that can be reused, such as gear boxes from vehicles, and then processes the rest into material streams for recycling. These can either be for a single material, like glass, or mixed material, like circuit boards from waste electronics. Introducing new materials into these systems can lead to contamination if there is no technology available to identify and separate them.

Reprocessing

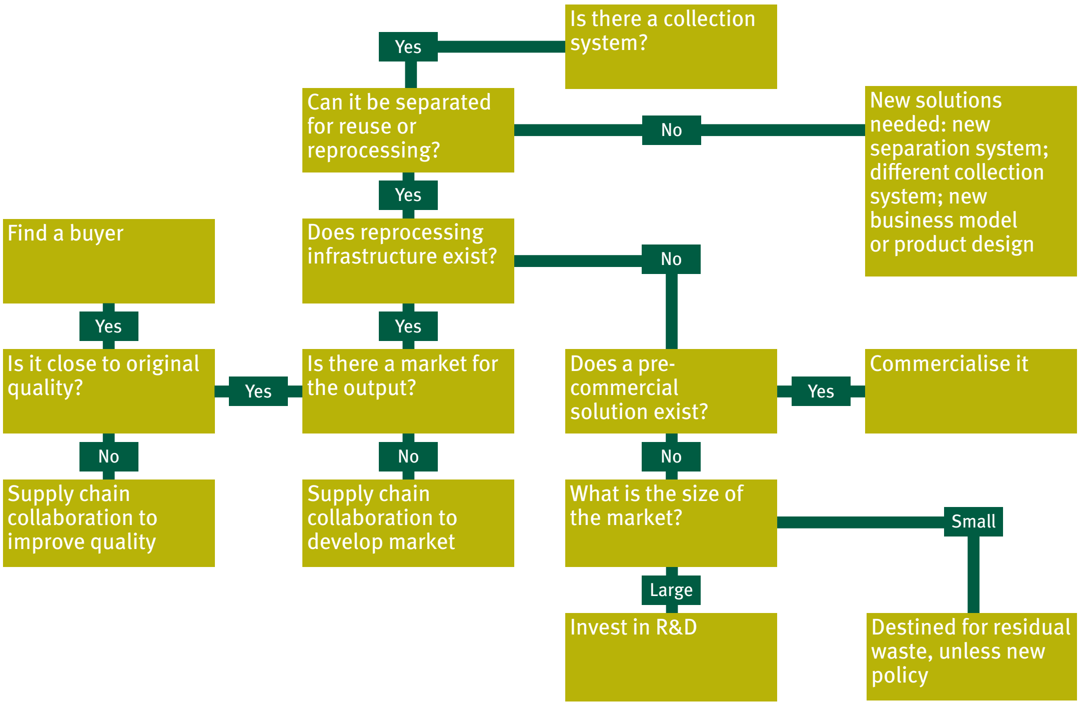
Outputs from the sorting process are converted into a new input for manufacturing. The ideal output of this stage is a material that can be used in exactly the same way as the original material. In practice, this is only consistently achieved for bulk metals, as the processes involved are more effective at dealing with contaminants. For all other materials, achieving a homogenous input is vital to producing a high value output. If the input material is too varied, then the output will only be suitable for downcycling, or valuable materials will be lost as waste products of the process, as is the case for rare earth metals when electronic wastes are shredded and sent for reprocessing.

How to improve current systems

When novel materials are used in products for which there is no collection system they are likely to end up in the residual waste stream. The exception would be if the material is valuable enough to change the economics of collection so it becomes viable to set up a reverse logistics and reprocessing system just for that material. Indeed, one of the development drivers for some materials is their superior recyclability eg plastics like polylactic acid (PLA) that can be depolymerised, avoiding contamination in a cost effective process. This might be because it has higher intrinsic value, or that it can be reprocessed at lower cost. In the absence of such clear market drivers, the only remaining driver is policy.

The decision flow diagram below offers a way of identifying where further material, product or market development is needed to maximise the circular economy potential of a novel material. It presents a series of questions about what happens to the product containing a novel material when it is thrown away.

Routes to a circular economy for novel materials



"There may be a solution at the pre-commercial stage that can recover more material value."

Options for recovery and reprocessing

If a material cannot be isolated and converted into a suitable input for reprocessing, there are a number of options to improve the existing system. One would be to invest in better sorting and identification technology, such as adding optical sorting equipment to a plastics recycling process. If this technology does not exist, it may be possible to avoid putting the material through the sorting system, for instance a product could be leased or provided as a service and returned directly to the manufacturer once no longer wanted. Another alternative would be to change the design so that higher value components can be removed and processed separately. This already happens for certain automotive components, but a component's value has to be higher than the labour costs of removing it.

If a material can be isolated from a waste stream but there is no facility to reprocess it, either because the technology does not exist or because it is uneconomic to transport it to the nearest facility, it will be necessary to look at the business case for developing a new facility. This will depend on the existence of suitable reprocessing technology, and both sufficient feedstock and a high enough market value of the reprocessed material. If these conditions are in place, then supply chain collaboration to help guarantee the supply of material for recycling and demand for the recycled material can help secure the necessary investment. If there is no technology under development, but a large predicted market, then industry can work with academics or other research organisations to develop a solution.

But, if the market for an end of life material is not expected to be large enough to sustain a new reprocessing facility, there is a case for policy makers to assess its environmental impacts and potentially intervene, either by deciding what applications it should be used for or by setting requirements for its recovery, as already happens for toxic or hazardous materials.

Finally, a material could be separated and reprocessed, but then its price will only be a fraction of its original value. This might be because the available reprocessing technologies cannot recover the material in its original form, eg grinding a carbon fibre composite up for use as low value filler in polymer applications rather than separating out the carbon fibres. Once again, there may be a solution at the pre-commercial stage that can recover more material value. If so, it will be worth considering the case for commercialising it.

It could be that recovered material is harder for manufacturers to use than the virgin alternative, in which case reprocessors could work with manufacturers or their suppliers to convert it into a form that suits their processes.

Collection system barriers

If there is no collection system it will be worth assessing whether the material could support a commercial collection and reprocessing supply chain. This will depend on both the monetary value of the material and the quantity available. If the material is insufficiently valuable or the total market size is too low to support a viable reprocessing facility, then it will only be recovered if policy drives it.

Three novel materials
Are they ready for a circular economy?

To develop a framework for identifying how to increase the value of recovered materials, we looked at three emergent technologies: carbon fibre reinforced polymers, bioplastics and additive manufacturing. In each case, we ask what would happen to something made from the material if it was thrown away today?

We consulted those involved in the whole supply chain for each material, from developers and users through to end of life collectors and reprocessors, to find out where technology development and deployment support could address the limitations of existing systems.

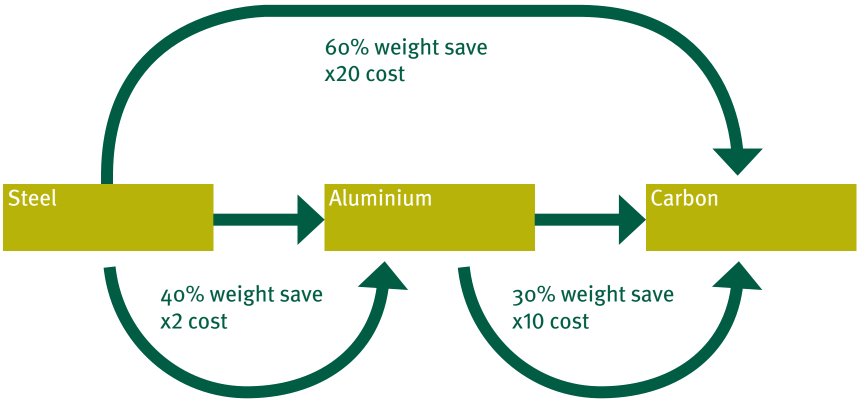
Carbon fibre reinforced polymers

Carbon fibre is not exactly new. It was invented in the 19th century and developed in its current form in the 1950s. What is new is the scale of demand. Thanks to their remarkable weight to strength ratio, the use of carbon fibre composites, a combination of carbon fibres and a polymer matrix, is growing rapidly in transport and renewable energy applications. For instance, they are now being used in Boeing's Dreamliner planes, BMW's i3 electric vehicles and Vestas' wind turbines.

Of these high growth applications, the end of life opportunities for carbon fibre used in cars is arguably the most important to assess. The relatively short service life of cars (ten to 15 years as opposed to over 25 years for planes and wind turbines) means they will be entering the waste stream in significant volumes in the near future. There is considerable scope for recovery as EU End of Life Vehicle regulations demand that all cars have to be collected for reprocessing and have 85 per cent of their materials reused or recycled.

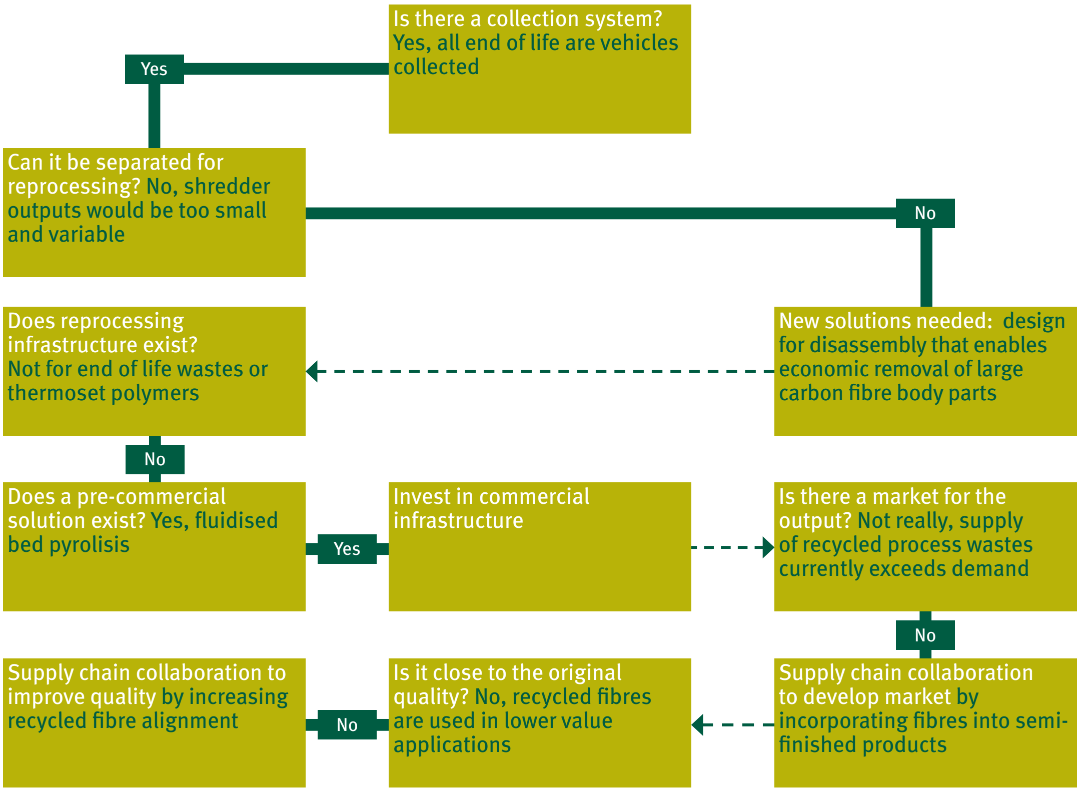
Successful recovery of carbon fibre from cars could generate a virtuous circle that increases the use of the material by the automotive sector. Carbon fibre is currently only used at the top end of the sector due to its high cost. Research by Jaguar Land Rover has shown that the cost of using carbon fibre to make parts can be 20 times more than using steel, and ten times more than aluminium, demonstrating the need to bring carbon fibre costs down before it can be used by the mass market.

How carbon fibre reduces weight but increases costs in car manufacturing[3]



Fibres collected from process wastes currently trade at a 20-40 per cent discount compared with virgin material.[4] Recovering good quality carbon fibres from end of life vehicles could significantly increase the supply of lower cost fibres and accelerate the transition to lighter, more fuel efficient vehicles.

What happens to carbon fibre used in cars today?



Is there a collection system? Yes, all end of life are vehicles collected

Yes

Can it be separated for reprocessing? No, shredder outputs would be too small and variable

No

New solutions needed: design for disassembly that enables economic removal of large carbon fibre body parts

Does reprocessing infrastructure exist? Not for end of life wastes or thermoset polymers

No

Does a pre-commercial solution exist? Yes, fluidised bed pyrolisis

Yes

Invest in commercial infrastructure

Is there a market for the output? Not really, supply of recycled process wastes currently exceeds demand

No

Supply chain collaboration to develop market by incorporating fibres into semi-finished products

Is it close to the original quality? No, recycled fibres are used in lower value applications

No

Supply chain collaboration to improve quality by increasing recycled fibre alignment

Barriers to a circular economy for carbon fibre reinforced polymers

The following barriers to recovering value from automotive carbon fibre reinforced polymers arise when using the existing vehicle processing and recovery infrastructure:

Material barriers

Pyrolysis is the only commercial technology for recovering fibres. But it does so at the expense of the polymer part of the composite (roughly a third of the material by weight), which is burnt off in the process with only a fraction of its embodied energy recovered as thermal energy.

Technology barriers

Existing sorting or reprocessing infrastructure is not well suited to fibre recovery. The sorting infrastructure depends on a shredding process that makes an output too fine to be used in existing reprocessing infrastructure. It would also be too variable in shape and too contaminated with other materials for pyrolysis facilities developed for more homogenous process wastes.

Market barriers

The market for good quality recycled carbon fibres is already oversupplied with fibres recovered from production wastes.

Opportunities for carbon fibre reinforced polymers in a circular economy

Our discussions with supply chain businesses for carbon fibre vehicles have identified the following circular economy solutions.[5]

Product redesign

Because carbon fibre composite components are not well suited to assembly systems developed for metal vehicles, such as bolting and welding, there is an opportunity to develop methods more suited to composites which also enable easier disassembly at end of life. This would need updated design software to take better account of the characteristics of composites.

Parts such as roofs or body panels could be removed to yield a stream of pure carbon fibre composite parts, either for reuse through repair operations or for reprocessing in existing pyrolysis facilities.

Alternative recycling technologies

There is an alternative recycling technology known as fluidised bed pyrolysis which has been shown to recover good quality fibres at a pre-commercial scale. This technology seems much better adapted to dealing with the variable nature of waste material streams than conventional pyrolysis, so should be tested with materials recovered from composite vehicles.

UK researchers are also looking into chemical recycling technologies for thermoset composites. These would have the advantage of recovering fibres with their original alignment and, therefore, enabling higher value recovery. But these technologies are at an early stage of development and, to become economically viable, they would have to achieve much shorter processing times.

Adding value to recovered fibre

Recycled carbon fibre cannot easily displace virgin fibre in existing applications, as it cannot provide the same functionality. So the immediate opportunity is to expand the range of applications in which recycled carbon fibre can be substituted for other materials. By integrating recycled fibre into non-woven mats, it can offer the same performance as glass fibre and aluminium but at lower weight.

To provide the same functionality as virgin fibre, recovered fibres need to be aligned so they can be packed more closely together when used in a composite. There are technological solutions for realigning fibres but none of them are developed beyond laboratory scale so further investment to commercialise them is required.

More value can be added to recovered fibres by incorporating them into intermediate products sold to car manufacturers. This can be achieved through collaboration between fibre recyclers and the companies that sell parts direct to car manufacturers (tier one suppliers), to map the properties of recovered fibres against the requirements of existing automotive components to identify the most suitable applications.. As there is no agreed methodology for assessing the quality of recovered fibres or the parts that use them, a satisfactory approach to certification is required so engineers and designers have the confidence to specify them.

"The immediate opportunity is to expand the range of applications in which recycled carbon fibre can be substituted for other materials."

Improving polymers for automotive composites

Most current carbon fibre reinforced polymers incorporate thermoset plastics, as they have a better performance to cost ratio than current thermoplastics and their physical properties make it easier to impregnate fibres. But thermosets are unrecyclable and require curing times that are a poor fit with existing automotive manufacturing processes.

By contrast, thermoplastic composites can be reshaped or remelted when heated, increasing their suitability for rapid manufacturing and recyclability. They also offer the potential for remoulding parts for reuse, although this would depend on being able to assess the integrity of used parts, particularly those recovered from a car that had been in an accident. Thermoplastics also have advantages in terms of impact and wear and tear of car parts.

PEEK is the only thermoplastic with performance characteristics equal to thermosets in automotive applications, but it is prohibitively expensive. To increase the feasibility of using thermoplastic carbon fibre reinforced polymers in automotive applications, materials science innovation is required. Possible goals for this include improving thermoplastics, by developing additives or new thermoplastics that can better coat fibre preforms (ie by making them less viscous), and improving the fibres by developing sizings (coatings that make fibres easier to use in manufacturing) for better carbon fibre-thermoplastic bonding.

Alternatively, the recyclability of thermoset polymers could be improved and research is underway on depolymerisable thermosets. But, in the specific context of the automotive industry, the challenge of long curing times mean such composites would still be poorly suited to manufacturing processes. Alternative polymer recycling technologies, such as solvolysis, are highly tailored to individual polymer types, which makes them better suited to dealing with wastes generated during the production process rather than at end of life, as they are much more homogenous.

Summary of recommendations for carbon fibre

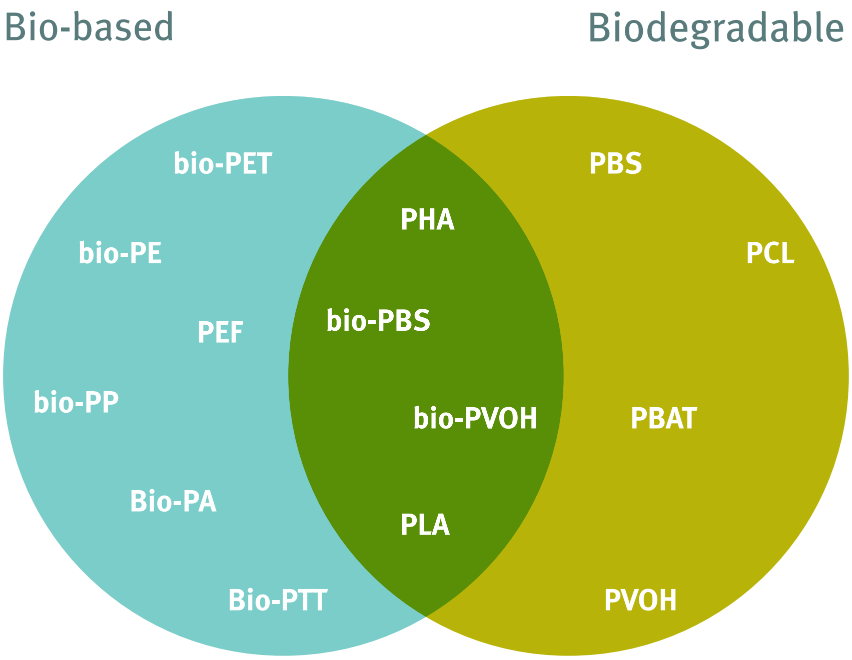
	Material innovation	**Technology development**	**Technology deployment**
Material barriers	Develop thermoplastic based composites for automotive applications. Research thermosets that can be recycled.	Scope the opportunity for remouldable parts for repair and reuse when developing thermoplastic composites, including a method for determining integrity of used parts.	
Technology barriers		Invest in the commercialisation of technologies to increase the alignment of recycled fibres. Design for easy removal of composite car components, including development of design software better suited to composites.	Commercialise fluidised bed recycling technologies for recovering fibres from thermoset composites.
Market barriers			Develop semi-finished components, incorporating recycled carbon fibres for easier use by manufacturers.

Bioplastics

Bioplastics refer to either biobased or biodegradable polymers. Biobased plastics are those made from plants or other non-fossil fuel feedstocks. They comprise both common plastic types, such as polyethylene (referred to as bioPE to distinguish it from its oil-based equivalent) and emergent plastics currently used at a small scale, like polylactic acid (PLA). Biodegradable plastics break down chemically into non-toxic compounds.[6] They include plastics that will break down under ambient conditions in the environment, such as polyhydroxyalkanoate (PHA), and those that will only biodegrade under the more aggressive conditions of an industrial composting or anaerobic digestion facility. For plastics intended to break down under industrial conditions there is a specific European compostability standard, which requires them to degrade fully in six to 12 weeks.

These two categories are not mutually exclusive, as some bioplastics are both biobased and biodegradable.

Common bioplastics and their properties

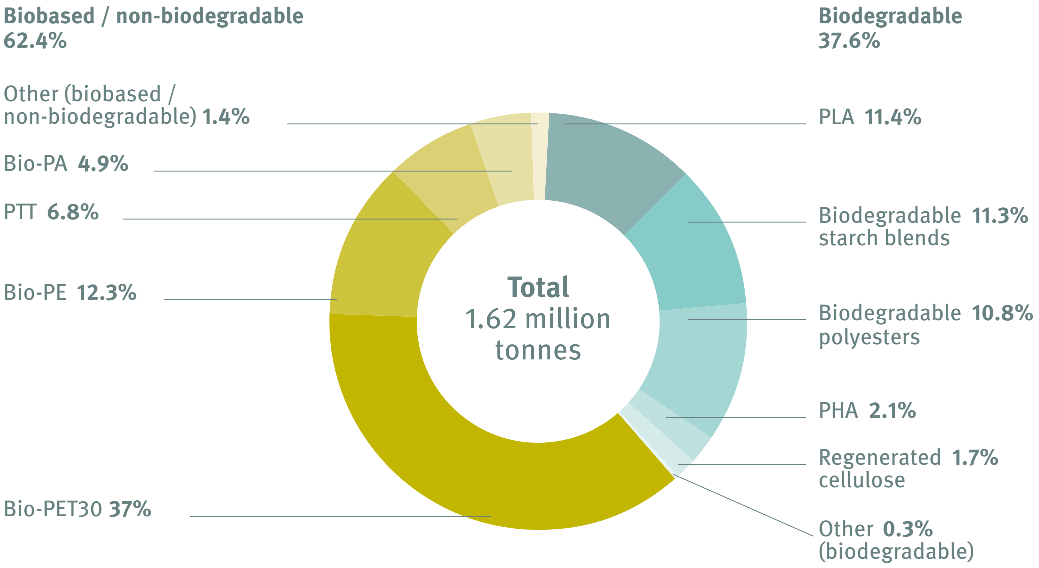


As with carbon fibre, many bioplastics are not new. Their novelty is based on a resurgence of interest because:

- they reduce dependence on fossil fuel feedstocks and have lower embodied CO_2 than their fossil fuel based counterparts, which can be used for marketing purposes, such as Coca Cola's Plant Bottle;
- some have better in life properties than plastics in widespread use, eg polythylene furanoate (PEF) has better barrier properties than the widely used polyethylene terephthalate (PET) for packaging applications; and, as manufacturing processes are evolving, some bioplastics are better suited to emergent technologies, eg PLA used in 3D printing;
- they have superior end of life properties, eg biodegradability is an obvious advantage for some plastic applications, especially for bioplastics that break down under ambient conditions; and they can be used in applications that are otherwise likely to cause environmental pollution, such as agricultural films; similarly, some bioplastics, like PLA, are recycled using processes that are more resilient to the contaminants that undermine much recycling of conventional plastics.

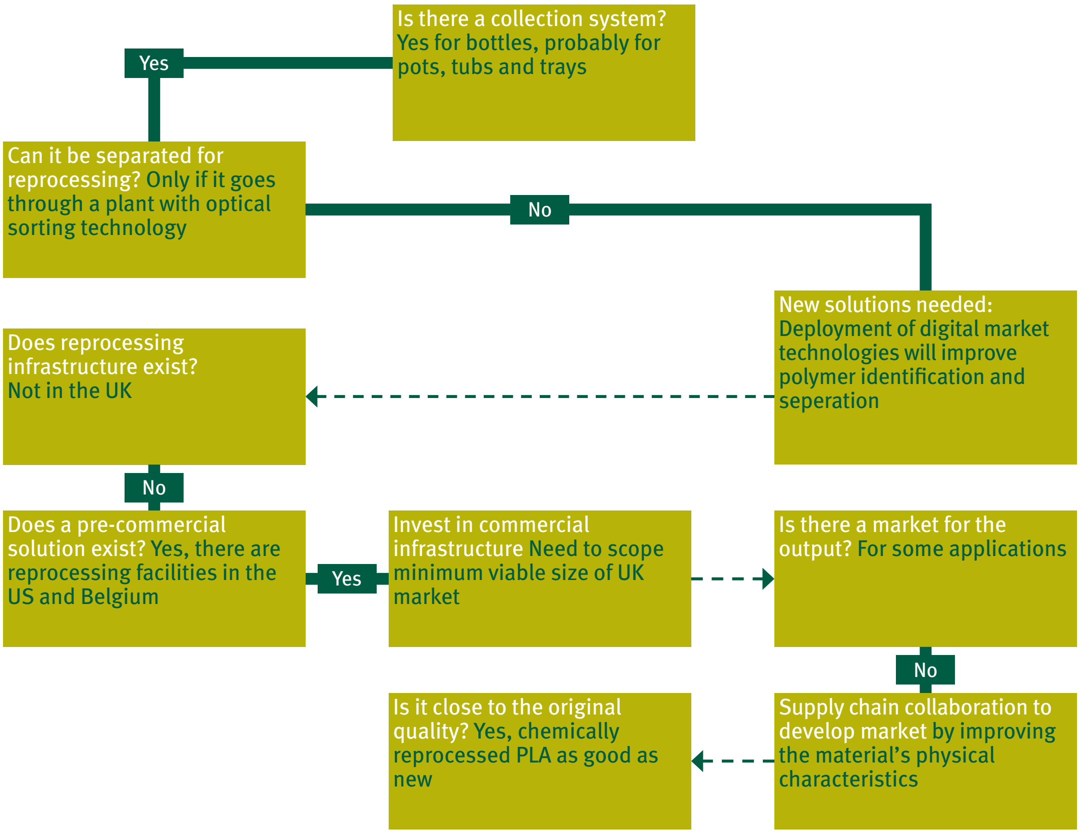
Despite growing interest, biobased plastics account for a tiny fraction (approximately 0.5 per cent) of the total plastics market, and the majority of the bioplastics market is made up of biobased versions of widely used plastics, as the chart below shows.

The bioplastics market in 2015[7]



As biobased plastics offer the same end of life challenges and opportunities as their fossil fuel based counterparts, they are not included further in this analysis, except in the context of the opportunity to synthesise them from waste feedstocks. We have focused on biodegradable bioplastics. To illustrate some of the circular economy threats and opportunities of bioplastics, we have used the example of the most widely used bioplastic, PLA, in the context of rigid household packaging.

What happens to biodegradable PLA plastic used in packaging today?



Is there a collection system? Yes for bottles, probably for pots, tubs and trays

Can it be separated for reprocessing? Only if it goes through a plant with optical sorting technology

New solutions needed: Deployment of digital market technologies will improve polymer identification and seperation

Does reprocessing infrastructure exist? Not in the UK

Does a pre-commercial solution exist? Yes, there are reprocessing facilities in the US and Belgium

Invest in commercial infrastructure Need to scope minimum viable size of UK market

Is there a market for the output? For some applications

Supply chain collaboration to develop market by improving the material's physical characteristics

Is it close to the original quality? Yes, chemically reprocessed PLA as good as new

"Introducing bioplastics to a waste material system can confound existing technology for sorting different polymer types."

Barriers to a circular economy for bioplastics

As the diagram above illustrates, there are a number of barriers to being able to make the most of the advantages of bioplastics. Moreover, even at current low levels of production, there are concerns about how the introduction of bioplastics will disrupt systems already recovering value from conventional plastics and about the land use impact of producing feedstock for bioplastic production.

Material barriers

In some contexts, bioplastics have lower functionality in use compared with conventional plastics. This limits the range of applications they can be used for and increases the likelihood that multiple polymer types will be used for similar applications which increases confusion when they are thrown away.

Technology barriers

Introducing bioplastics into a waste management system can confound existing technology for sorting different polymer types, especially if they are based on physical processes. For example, sink and float systems for separating bottles made of PET (which sink) from those made of HDPE (which float) are contaminated by PLA. Failure to separate bioplastics from other polymers prevents the recycling of bioplastics and contaminates the recycling of other polymers.

Most biobased plastics are also made from primary feedstocks (crops grown for the specific use as inputs into a bioplastic manufacturing process). Whilst using these feedstocks has lifecycle CO_2 advantages compared with fossil fuel based production, there are concerns over the wider environmental impacts of agricultural production and the use of land for producing non-food outputs, a subject that has been made more sensitive by biofuels production.

Market barriers

Not all plastic packaging is collected for recycling. Whilst almost every local authority in the UK collects plastic bottles, only a small majority collect other rigid plastics like pots, tubs and trays, and very few collect plastic films. Even if all the bioplastics on the market were collected, there is currently insufficient supply to sustain a viable closed loop recycling plant.

Opportunities for bioplastics in a circular economy

A number of complementary system changes are required to overcome the barriers, and exploit the advantages of bioplastics, whilst minimising the disruption to existing plastics recovery.

The use of waste biomass as feedstock

Using secondary feedstocks (waste or low value by-products of another process) provides an opportunity to make biobased plastics without the environmental impacts of agriculture. It also increases the likelihood of securing UK production, or licensable intellectual property owned by UK companies, given the current dominance of Brazilian sugar or subsidised US corn as feedstocks for current bioplastic production.

But switching to organic waste feedstocks, like household food waste or the by-products of food and drink production, is far from straightforward. As with any other waste feedstock, economic viability will depend on the volume, quality and cost of transportation to reprocessing facilities, as well as the disposal costs of any wastes produced. This can be further complicated by seasonal changes in availability.

Also, many of the processes that convert waste feedstocks into the chemicals needed to make bioplastics depend on enzymes that can themselves be very resource intensive to produce.

To facilitate the use of bioplastic waste feedstocks, it is necessary to:

- map available feedstocks, including the quantity and any seasonal variation in their availability;
- identify the most straightforward conversion pathways from particular waste streams to particular bioplastics, eg PLA from dairy waste;
- prioritise the production of platform chemicals, ie compounds from which many other chemicals can be made, from high volume feedstocks, such as using cellulose from agricultural wastes to produce ethanol;
- scope the suitability of outputs from other bioeconomy processes, such as biofuel production or anaerobic digestion, as inputs to bioplastic production. A scale that measures the ease of use of different waste feedstocks relative to sugar (the easiest biomaterial to convert) would help with this.

Close collaboration between the food production and manufacturing sectors is necessary to increase the use of waste biomass as feedstock. And the public sector should be involved to convene, provide information and fund research and development.

Improving sorting processes

To prevent contamination of established recycling streams, plastics have to be identified and sorted by polymer type. Whilst this can be achieved using Near Infrared optical sorting technology, not all facilities have this and, even where they do, the technology can be confused by products containing dark pigments or completely covered by labels. Fortunately, there are a number of solutions recently introduced to the market, or close to market, that use optical technologies to make sorting more effective. Digital watermarks and fluorescent inks are being developed to enable much finer grained sorting of plastics, for instance, not just by polymer type but also by whether it is approved for food contact.

Although these new technologies are not the whole solution, as not all plastics are sorted using optical equipment, they would increase the returns available from investing in expensive sorting equipment. They would also complement the proposals to collect rigid plastics in all the local authorities of England, Wales and Scotland. [8] And the business case is further supported by higher recycling targets in Wales and Scotland (England's future recycling targets are uncertain as they have been driven by EU legislation). Universal rigid plastics collection, if coupled with enhanced optical sorting technologies, would help address concerns about contamination.

Selective use of biodegradable plastics

Until optical sorting of collected plastics becomes ubiquitous, it would be reasonable to limit the use of biodegradable plastics to applications that are not currently recycled and where their properties address wider system problems, such as facilitating food waste collection. Possible examples include food packaging and disposable cutlery.

Related to this is the challenge of improving people's understanding of what to do with a wider variety of plastics. Sorting requirements for recycling collections can already cause confusion, eg when you can recycle plastic bottles but not plastic pots, tubs and trays. Any system that relies on people correctly separating apparently similar things is vulnerable to high levels of contamination.

Whilst communication campaigns can help, one solution is to standardise polymer types by application. Industry is already engaging in voluntary discussions as part of the Plastics Industry Recycling Action Plan (PIRAP) convened by WRAP.[9]

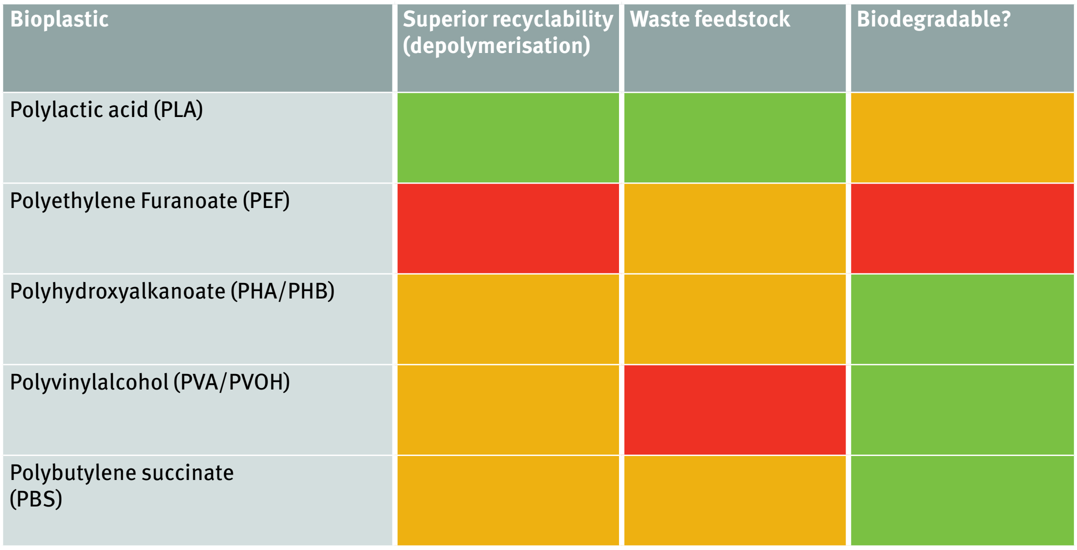
In other contexts regulation can help. For example, both France and Italy require all single use carrier bags to be made from biodegradable plastic and Scotland's commercial food waste collection regulations have provided a significant boost to demand for biodegradable food service products.

Realising the potential of bioplastics

To prepare product systems for the introduction of bioplastics, especially biodegradable plastic, and to construct a business case for developing reprocessing infrastructure, it is helpful to scope what materials are likely to be used for different applications.

We have identified a group of bioplastics that are at various stages of commercial development thanks to their in life or end of life advantages. The table opposite provides a rough traffic light analysis of how well they might perform in a circular economy.[10]

Circular economy opportunities for emergent bioplastics



Bioplastic	Superior recyclability (depolymerisation)	Waste feedstock	Biodegradable?
Polylactic acid (PLA)	🟩	🟩	🟧
Polyethylene Furanoate (PEF)	🟥	🟧	🟥
Polyhydroxyalkanoate (PHA/PHB)	🟧	🟧	🟩
Polyvinylalcohol (PVA/PVOH)	🟧	🟥	🟩
Polybutylene succinate (PBS)	🟧	🟧	🟩

This shows that most bioplastics are being developed for their end of life advantages, particularly their biodegradability. Many of these bioplastics also have the potential to be made from waste feedstocks or recycled through depolymerisation, although realising these opportunities will depend on new technologies and infrastructure. The exception to this is PEF, which is being developed because of its superior in life performance compared to the conventional plastic, PET. PEF's maker, Avantium, claims that it can be recycled with PET in small quantities without any impact on the quality of the recycled PET. If and when PEF usage gets to a level where it is undermining PET recycling, then it should also be economic to have specific PEF recycling infrastructure. The level at which this tipping point is expected to occur is five per cent of the waste stream.

But biobased plastic will not be adopted solely on the basis of its end of life potential, especially not in engineering applications. Performance in life must be at least as good as the plastic it is displacing. To show where bioplastics could displace conventional plastics, the following analysis compares their functional capabilities with the most widely used plastics.

Scoping applications for emergent bioplastics

Bioplastic	Current plastic							
	PET	HDPE	LDPE	PP	PS	PVC	ABS	PA
Polylactic acid (PLA)	🟧	🟧	🟧	🟩	🟩	🟥	🟧	🟥
Polyethylene Furanoate (PEF)	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Polyhydroxyalkanoate (PHA/PHB)	🟩	🟧	🟧	🟩	🟩	🟧	🟩	🟥
Polyvinylalcohol (PVA/PVOH)	🟧	🟩	🟩	🟩	🟥	🟥	🟥	🟥
Polybutylene succinate (PBS)	🟩	🟥	🟩	🟩	🟩	🟥	🟥	🟥

This is only a starting point for identifying where bioplastics might replace conventional plastics. Analysis of the interaction of novel materials with existing systems has to be done in the context of a specific product; this is not least because a bioplastic might be substitutable in some applications, eg PLA for PET in water bottles, but not others, as PLA cannot be used in place of PET for higher temperature applications as it deforms at temperatures above 60 degrees centigrade.

Our analysis is largely derived from comparative studies of packaging applications as this is where there is most publicly available information. To enable wider sector and product specific analyses, much more information should be made public.

Future development

Although our compatibility analysis suggests that most conventional plastics have a suitable bioplastic alternative, at least for packaging, there are few applications where current bioplastic formulations can provide exactly the same functionality as conventional plastic. Better functionality can be achieved by using blends of bioplastics but, unless these are standardised so they can be recycled as a blend, they will present the same recycling challenges as any mixed material. The exception to this is if both materials are biodegradable and so can be treated by composting or anaerobic digestion.

More material science research is required to improve the functionality of bioplastics. Targets for this should include additives which improve the performance of existing bioplastics and new bio-monomers, from which new bioplastics can be made.

In an interesting crossover with carbon fibre, there is hope that new bioplastics might prove effective for composite applications. If such polymers were depolymerisable (ie able to be broken down into their chemical constituents) it could help to address the challenge of recovering materials from composite applications.

Another area of development is the use of bioplastics in 3D printing. PLA is a popular material for this, and it is possible that the true advantages of bioplastics will be seen more quickly in emergent applications rather than by displacing conventional plastics.

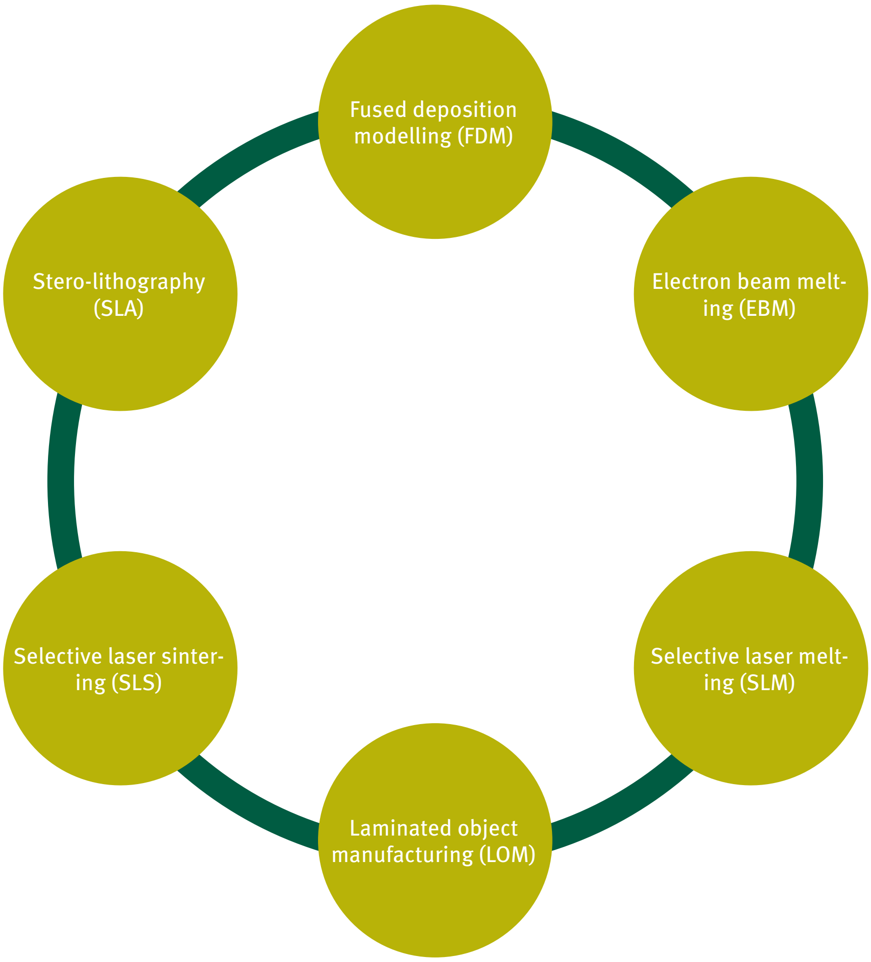
Summary of recommendations for bioplastics

	Material innovation	**Technology development**	**Technology deployment**
Material barriers		Match the in use performance of bioplastics to current plastics sector by sector.	
Technology barriers		Invest in the commercialisation of platform chemical production from high volume waste feedstocks.	Invest in digital marker technologies for improved polymer identification and sorting.
Market barriers	Scope the availability and viability of waste feedstocks, including by-products of other bioeconomy processes.		Implement universal collection of all rigid plastic packaging. Engage the supply chains sector by sector to agree the most suitable applications for bioplastics.

Additive manufacturing

Additive manufacturing (AM) is a term that embraces a variety of techniques for depositing or layering (laminating) materials into 3D forms, hence it is often colloquially referred to as 3D printing.[11] The characteristic that unites them is that they produce an object by building it up layer by layer rather than removing material from an initial block, which is known as subtractive manufacturing.

The six technology types for additive manufacturing

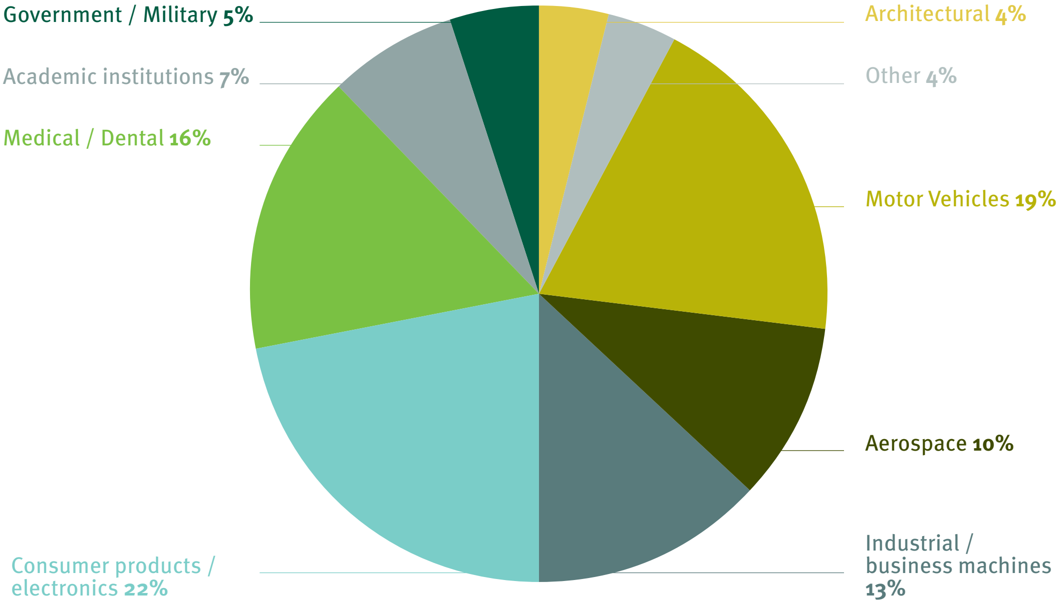


AM can be performed with any material that can be melted or shaped, including plastic polymers, metals, wax, wood, ceramic materials, chocolate and even human tissue. All are driven by increasingly sophisticated computer aided design (CAD) software.

AM devices can be the size of a truck, as in those being developed to manufacture whole buildings, or they can fit onto a desk, such as those already in use in schools and households to make artworks, toys and parts.[12]

Use of AM has grown rapidly over the past three decades, from its first commercial application in 1987 to a five billion dollar global market in 2016.[13] It has flourished in the sectors that benefit the most from its superior ability to produce bespoke objects at higher speed and lower cost than conventional manufacturing.

Revenue split of additive manufacturing equipment customers[14]



This technology has the potential to support the transition to a circular economy across a wide range of sectors. Because of this diversity, we have not carried out a flow diagram analysis to identify barriers to the circular economy for a particular product made using AM. Instead, we have identified three characteristics of AM that are of particular relevance to a circular economy:

1. Rapid prototyping and innovative design
2. Small batch manufacturing
3. More resource efficient production

Opportunities for additive manufacturing in a circular economy

1. Rapid prototyping and innovative design

“Using AM for manufacturing as well as prototyping could mean products are fundamentally better suited to a circular economy.”

Product redesign for durability, repairability and recyclability

The ability to make bespoke objects, rapidly and relatively cheaply, means that AM is already used widely for prototyping. Fit and assembly prototypes, used to work out how to manufacture a product, are the second most common application of AM technologies. One of the current barriers to a more circular economy is that most products are not designed with the circular economy in mind, so using AM prototypes to lower the costs of product redesign should help to extend the range of products suitable for reuse, repair and recycling. This could be accelerated by increasing the access of designers to AM, such as through the ‘Fab Lab’ movement.[15]

Prototyping with AM is typically used for products that will then be manufactured using conventional subtractive techniques. But using AM for manufacturing as well as prototyping could mean products are fundamentally better suited to a circular economy. Because complex structures such as matrices, linked or perforated forms become possible without complex manufacturing processes, this technology could enable products to be designed to fit better with circular economy business models. Examples include fixings and fastenings that avoid the need for adhesives to improve disassembly, and more complex structures that provide the same performance with a single material as otherwise delivered by an unrecyclable combination of materials.

Supporting remanufacturing

Remanufacturing and repair are emerging as uses for AM, most strikingly for items that had been considered beyond repair, such as bearings and seals.[16] This could change the economics of business models in sectors where remanufacturing has struggled to gain traction. But the hardware involved is often too expensive for smaller companies who make up the majority of remanufacturers. Given this, the immediate opportunity is more likely to be amongst original equipment manufacturers, who might consider adding remanufacturing as a service to their customer offer.

A better understanding is needed of which AM technologies are best suited to remanufacturing and in what sectors. This will help to identify where AM technologies used for primary production can be straightforwardly applied to remanufacturing the same products. It will also help to determine whether a particular AM technology can be applied to remanufacture components from a range of sectors, which would increase the viability of independent remanufacturing businesses. Because components produced using AM often require post production finishing, such as grinding or polishing, the emergence of combined additive and subtractive manufacturing machinery is of particular interest. This combination has already been used to repair wind turbine blades.[17]

2. Small batch manufacturing

Production of low volume and discontinued spare parts

Producing parts is already the most common application for AM technologies.[18] For the aerospace, automotive and biomedical sectors, it has enabled both simplification of production, such as printing a single part that previously required welding separate components together, and it has also increased specificity, such as prosthetic limbs developed specifically for the user.

One barrier to keeping products in working order for longer is the limited availability of spare parts, which AM could help to overcome. For manufacturers, keeping a stock of spare parts is a cost, so they hold only a limited inventory and will usually stop holding or producing spare parts for discontinued products, especially once they are out of warranty. Because AM can be used for small production runs at low unit cost, there is potential to produce spare parts on demand and lower the cost of maintaining products for longer.

The decreasing cost of AM hardware will also increase the viability of independent repair businesses and householders producing their own spare parts and carrying out simple repairs.

However, there are some major questions about using AM to produce spare parts. Perhaps the most important is how suitable the technology is for producing parts that were not originally created using AM, ie where there is no digital design file. For example, an exploratory study by BMW found that the parts produced using AM cost almost five times more than available classic car spares, and did not accurately replicate the original part.[19]

One determinant will be the ease of retrospectively developing CAD files for AM. An enabler for this will be greater availability and sophistication of 3D scanning technologies, but this raises other questions around copying designs with intellectual property protections and warranty restrictions for products that incorporate third party parts.

As with remanufacturing, it is possible that the new capabilities offered by AM will stimulate new business models amongst manufacturers that can address intellectual property and warranty concerns. The opportunity to license access to digital design files, with requirements on the hardware and feedstock used for parts, could stimulate a profitable independent parts supply chain.

3. More resource efficient production

One of the obvious attractions of AM is its potential to reduce the amount of material used in production. By building something up rather than removing excess material, in theory only the amount of material required by the final product is used. AM is also able to use material efficiently through hollow parts and selectively applying material to load bearing regions.

However, lifecycle studies suggest that the material savings in finished products might be offset by higher embodied energy in the materials used, particularly in the use of metal powders, and because there is wastage associated with failed prints and unused printing materials. In a comparison of making the same object out of nylon using one AM technique, selective laser sintering (SLS), and one conventional manufacturing technique, SLS was found to be less energy efficient at larger production volumes.[20]

The environmental impact of materials used in AM could be reduced by using more recycled feedstocks and better recovery of unused prints and printing materials. There are already processes for turning waste plastics, including previously printed objects, into suitable inputs for fused deposition modelling printers. But highly recyclable and recycled materials that could be used in 3D printing will only be suitable for a limited range of applications, not least because understanding the functionality of the recycled materials is still being developed.

Making the most of recycled and recyclable materials depends on finding the most suitable applications for them, and improving the quality of recycled inputs to increase the range of applications they can be used for. It will also depend on effective business models for collecting waste prints and other sources of the same material, to lower the cost of producing recycled materials and enable them to compete with virgin polymers. Developing these systems and business models should be prioritised based on which applications have the greatest lifecycle advantages for using recyclable and recycled plastics.

A circular economy for additive manufacturing

How much AM can help with designing and manufacturing products better suited to a circular economy will vary with the type of product in question. A review is needed of the capacity of the technology to meet the structural, material and cost requirements of products in different sectors. The table opposite shows the sectors where AM is already delivering improved circular economy outcomes.

Application	Technique	Scale	Sector	Example
Parts	Fused deposition modelling	Commercial	Aerospace	The Airbus A350 XWB has over 1,000 3D printed parts incorporated.
		Small scale commercial	Consumer goods	Thingiverse is an online platform for thousands of designs including toys, gadgets and models that users can print by themselves or through 3D hubs.
	Powder bed fusion	Research	Automotive	A spokesperson for Audi has stated "One of our aims is to use 3D metal parts for regular car production."
		Commercial	Aerospace	General Electrics' new LEAP engine has 19 3D printed fuel nozzles.
Spare parts	Fused deposition modelling	Hobbyist	Consumer goods	An individual has used 3D printing to fix a broken part on fridge.
	Powder bed fusion	Hobbyist	Consumer goods	An individual has used 3D printing to replace a broken car part.
Rapid prototyping	Fused deposition modelling	Commercial	Consumer goods	Salomon has used 3D printing for show protoyping.
	Powder bed fusion/ fused deposition modelling/ Sterolithography	Commercial	Automotive	Jaguar Land Rover use 3D printed parts in prototype vehicles including the F-type coupe.
	Stereolithography	Commercial	Architecture	Hobs produce detailed architectural models using a 3D printer.
Remanufacturing	Direct energy deposition	Research	High value engineering	Hybrid Manufacturing Technologies' dual 3D printing and CNC machine system can be used to repair turbine blades.
Multiple materials	Fused deposition modelling	Commercial	Prototyping	Multicolour and material printing are used to make prototypes closer to final product.
	Fused deposition modelling	Research	Complex meta-materials	MIT has created a 3D printing system for use in researching multiple materials at high precision, ultimately to create complete final products.
Electronics	Fused deposition modelling	Research	Research	The voxel8 printer can print silver ink to use in electronics including creating a component to test the functionality of other electronic components and concept designs.

The potential for AM to help the transition to a circular economy is most developed in the automotive and aerospace sectors. Both sectors already incorporate many circular economy principles because of the high costs and long service lives of the hardware involved. But, for other sectors, it will be necessary to work out what the barriers are to using AM and how further research and development can help. If the barrier is cost then it is likely to be resolved eventually as the cost of the technology decreases over time. Where the obstruction is an inability to meet material requirements, such as complex electronics, more targeted research and development is necessary.

Barriers to a circular economy for additive manufacturing

Despite its potential to support a circular economy, some characteristics of AM could also undermine it by increasing the complexity of materials used in combination with each other, and confounding established value recovery systems.

More capacity to produce unique and complex multimaterial products

The obvious concern with the growth of additive manufacturing is its potential to allow 'mass customisation'. Systems that recover value from discarded products depend on large quantities of similarly constructed products to be financially viable. The growing ability of AM processes to integrate varied combinations of materials into the same type of product will reduce the ability of recyclers and reprocessors to separate and recover useful material.

Customisation of form might not be a threat, for instance personalised designs for a toy made from just one polymer. However, customisation of material type, for instance the same kind of toy made from bespoke polymer combinations would be more difficult to deal with.

To avoid increasing the number of unrecyclable products, sector by sector analysis should be done to identify which material combinations produced by AM, and in which applications, should be avoided.

Potential contribution to e-waste

The market for domestic 3D printing machines is still relatively niche. According to a March 2015 estimate, 100,000 consumer 3D printers had been sold in the UK, compared with more than two million conventional consumer printers in 2013 alone.[21] But, with predictions that half of all households in the US and Europe will have 3D printers by 2030, it is possible they will contribute to the growing e-waste problem.[22]

One way to avoid this would be to expand access to the technology through leasing or service-based business models. These approaches are widely used for the supply of commercial conventional printers, due to the relatively high cost of the hardware. Such services are typically offered direct by the printer manufacturers or by specialised printing services companies. It is also possible to access 3D printers through 3D hubs, new platforms for linking people who want to print locally.

But, as 3D printers become increasingly affordable, consumer electronics retailers will determine whether people access the technology through leasing or buying. One way of avoiding the most wasteful aspects of conventional printers would be to prevent limiting the compatibility of printer consumables with hardware. In the conventional print market, hardware is often sold as a loss leader because manufacturers restrict the compatibility of third party ink cartridges. This drives up the cost of the consumables and lowers the incentive to keep the hardware. Ensuring 3D printers can accept inputs from a wide range of sources would limit this practice.

Finally, as the hardware is still being developed, reuse and remanufacturing potential could be maximised at the design stage. More durable hardware would increase the profitability of leasing or service-based business models. The table below highlights the next steps to ensuring AM becomes an enabling technology for a circular economy, rather than one that undermines it.

Summary of recommendations for additive manufacturing

	Material innovation	**Technology development**	**Technology deployment**
Material barriers		Scope opportunities to replace material complexity with structural complexity. Increase the capacity to recycle failed prints and unused printing materials. Invest in reprocessing technologies for unused printing materials.	
Technology barriers	Invest in producing higher quality recycled materials for use in 3D printers.	Develop alternative fixings and fastenings for hard to disassemble parts or products. Develop capability in combined additive and subtractive manufacturing to expand the range of products and applications that can be remanufactured.	
Market barriers	Prioritise customisation that uses the same material for the same product type. Scope recovery systems for failed prints and unused printing materials.	Expand the range of legacy parts that can be produced using AM, through improved 3D scanning technologies and the availability of CAD files. Develop licensing business models to allow third parties to produce parts.	Apply rapid prototyping capacity to develop products with good ecodesign characteristics. Maintain the availability of spare parts for products originally produced using AM.

Recommendations for those developing novel materials

We have shown how the UK could increase resource efficiency in relation to three specific novel materials. But we have highlighted that, if circular economy considerations are not built in from the start, it could set back progress on recycling and valuable resources will be lost to the economy.

To solve these issues we recommend the following for UK research and development:

Opportunities for carbon fibre reinforced polymers

The UK has the capacity to be a leading innovator in recoverable carbon fibre composite materials.

Improve the materials

A challenge for the research councils (the EPSRC and the BBSRC) is to improve the suitability of thermoplastics for composite applications and improve the recyclability of thermosets, to develop recyclable polymers for use in composites. This requires development of new polymers or new additives.

Improve the technology

A challenge for Innovate UK or the High Value Manufacturing Catapult is to help commercialise the technologies proven at laboratory scale and develop new recycling technologies to recover high quality fibres from discarded products. It is also a business model challenge to secure sufficient feedstock for commercial reprocessing infrastructure. For the automotive industry, collaboration with manufacturers and end of life vehicles handlers may be the best solution to this.

Develop the market

The EPSRC is funding research into new technologies to realign fibres, to create higher value recycled outputs. But the challenge for Innovate UK, the High Value Manufacturing Catapult and the Knowledge Transfer Network is to help develop the markets for these fibres.

Opportunities for bioplastics

The market for bioplastics is growing fast, in spite of controversies over using agricultural feedstocks and the potential contamination of recycling streams. Thanks to the UK's competitive advantage in biotechnology and growing expertise in innovative recycling technologies, there is an opportunity to increase our share of this market whilst addressing the risks.

Improve the materials

A challenge for all the research councils is to improve the versatility of bioplastics so they can deliver the same level of performance as conventional plastics.

A successful recycling supply chain in the UK would mean cheaper inputs for manufacturers

Improve the technology

The BBSRC should support waste conversion technologies, like bacteria that can convert byproducts of pulp and paper production into platform chemicals. WRAP have led work on digital fingerprinting and identification technologies to improve the sorting and separation of polymers, and these should also be applied to bioplastics.

Develop the supply chain

WRAP should convene discussions with supply chain businesses to promote the use of bioplastics in sectors where end of life advantages are maximised, eg compostable agricultural films, and contamination of existing recycling systems is minimised. Innovate UK also has a role in developing and supporting supply chains that can match wastes with users.

Oportunities for additive manufacturing

Additive manufacturing is different to the two other materials we have studied, in that it is a novel process which embraces a wide range of techniques and a growing range of materials. How additive manufacturing contributes to, or undermines, the circular economy will vary from sector to sector. But it has clear circular economy potential in enabling repair, remanufacturing, reuse and recycling.

Exploit the advantages

The EPSRC, Innovate UK, the High Value Manufacturing Catapult, and the pioneering companies they work with, should focus on exploiting the advantages of AM over conventional design and production systems. In particular, public funding to support AM in making finished parts should consider how to increase the availability of spare parts and ensure parts are suitable for remanufacturing. Research into producing whole products should look at how to make them easier to take apart and repair.

Improve recycling and reduce waste

The same organisations should work on solving AM's possible downsides, ie increased material complexity at the expense of recycling; and waste from failed prints, unused printing materials and discarded 3D printing machines. Public support should be given on the condition that the recyclability of the products developed is considered. And help should be given to develop the technologies, supply chains and business models that will increase recovery of waste materials and the use of recycled inputs.

Conclusions

The need for a business response to global resource constraints is already recognised in the UK's manufacturing strategy.[23] Those countries and companies that meet this challenge will enjoy a competitive advantage at home and abroad. Taking carbon fibre as an example, a successful recycling supply chain in the UK would mean cheaper inputs for manufacturers, helping them to break into new markets for applications where the material was previously too expensive and compete better on cost and quality. Failing to develop this will leave UK manufacturers almost entirely dependent on imports, increasing their exposure to global price volatility. It also closes off the chance to export UK expertise in both recovering and reusing fibres.

From our study we have concluded three simple overarching principles for developing novel materials in a way that will make them circular economy ready:

Think ahead
Identify, during the development phase, what could enhance or prevent the circular use of a novel material at mass market scale to avoid problems in recovering value and enable a longer and more useful life to be designed in at the outset.

Collaborate
Collaborate along the supply chain to make the most of opportunities to maximise a material's value. Systems can then emerge that no single company could achieve alone. For instance, co-operation between reprocessors and manufacturers would make sure that recovered materials fit with existing production processes.

Public sector support
Publicly funded research for the development and deployment of novel materials must always take their end of life recovery into account. And public policy should promote the highest value, least environmentally damaging recovery systems rather than low value options like landfill and incineration.

Annex 1
Carbon fibre reinforced polymers workshop participants

Keith Freegard	Axion Consulting
Roger Morton	Axion Consulting
Dr Gary Leeke	University of Birmingham
Peter Cottrell	Department for Business Innovation and Skills
Marco Gehr	ELG Carbon Fibre
Prof Kevin Potter	Centre for Innovative Manufacturing in Composites
Robert Felstead	Engineering and Physical Sciences Research Council
Emily Coats	Green Alliance
Jonny Hazell	Green Alliance
Julie Hill	Green Alliance
Nick Cliffe	Innovate UK
Eissa Senan	Jaguar Land Rover
Prof Carolyn Roberts	Knowledge Transfer Network
Prof Steve Pickering	University of Nottingham

Annex 2
Bioplastics workshop participants

Mike Everard	Aquapak Polymers
Michael Booth	Biotechnology and Biological Sciences Research Council
Jim Song	Brunel University
MinNah Tong	Dyson
Robert Felstead	Engineering and Physical Sciences Research Council
Jonny Hazell	Green Alliance
Julie Hill	Green Alliance
Jasper Keech	Green Alliance
Simon Buckingham	High Value Manufacturing Catapult
Nick Cliffe	Innovate UK
Prof Carolyn Roberts	Knowledge Transfer Network UK
Adrian Higson	National Non-Food Crops Centre
Paul Darby	Novamont
Tony Breton	Novamont
Scott Knowles	ObjectForm
Adrian Whyle	Plastics Europe
Richard Murphy	University of Surrey
Tim Bugg	Warwick University
Marcel Arsand	WRAP

Annex 3
Additive manufacturing technologies

Technique	Process	Materials
Vat photopolymerisation: forms are produced from a vat of material by UV curing of the form in layers	Stereolithography (SLA)	Liquid polymer Resin
	Digital light processing (DLP)	Ceramic, metal
Material jetting: material is jetted onto a build platform, like a 2D ink jet printer	Muliti-jet modeling (MJM)	Polymers, wax, composites, metals
Material extrusion: material is pulled through a nozzle and deposited in layers on a build surface	Fused deposition modeling (FDM)	Polymers, wood, silver ink
Powder bed fusion (PBF): covers several techniques: uses laser, electron beams or other heat source to melt and fuse material powder into layers	Electron beam melting (EBM)	Metals
	Selective laser sintering (SLS)	Metals, Nylon
	Selective heat sintering (SHS)	Nylon
	Direct metal laser sintering (DMLS)	Metals
Binder jetting: jets alternate layers of powdered material and binder to make the form	Powder bed and inkjet head 3D printing (PBIH)	Metals, polymers, ceramics
	Plaster-based 3D printing (PP)	Metals, polymers, ceramics
Sheet lamination: binds material together in layers, by welding or adhesive	Laminated object manufacturing (LOM)	Paper, plastic and some sheet metals.
	Ultrasonic consolidation (UC)	
Directed energy deposition (DED): like extrusion, but the nozzle can work at different angles	Laser metal deposition (LMD)	Metals

Endnotes

1 Zero Waste Scotland, 2015, *Circular economy evidence building programme – remanufacturing study*

2 Reproduced from *Resource resilient UK*, 2013, Green Alliance

3 Adapted from the Jaguar Land Rover presentation, 28 April 2015 'Carbon fibre in mass automotive applications – challenges and drivers for composites', Franco-British symposium on composite materials

4 G Gardiner, 2014, 'Recycled fiber update: Closing the CFRP lifecycle loop', *Composites World*, www.compositesworld.com/articles/recycled-carbon-fiber-update-closing-the-cfrp-lifecycle-loop

5 See Annex 1 for details of workshop participants

6 Biodegradability has been controversial because of oxo-degradable plastics laying claim to the term. These are plastics that break down physically, ie into smaller chunks of the same thing, rather than chemically (into different compounds than the original polymer). We have excluded oxo-degradable plastics from this analysis as physical degradation causes more environmental damage than chemical degradation.

7 Adapted from Institute for Bioplastics and Biocomposites, nova-institute, 2015, *European Bioplastics*

8 The WRAP/Defra collections vision,2016; *Welsh collections blueprint*,2011; and Scotland's *Household charter*,2015

9 WRAP, 2016, *Plastics industry recycling action plan* (PIRAP), WRAP

10 See annex 2 for details of workshop participants who reviewed these ratings

11 See table in annex 3 for a full list of additive manufacturing technologies

12 DUS Architects in the Netherlands led an international consortium to build a house from 3d printed parts, including whole rooms. See http://3dprintcanalhouse.com/about-the-3d-print-canal-house for further detail.

13 Wohlers Associates, 2016, *3D printing and additive manufacturing state of the industry: 2016 annual worldwide progress report*

14 Wohlers Associates, 2013, *3D printing and additive manufacturing state of the industry: 2013 annual worldwide progress report*

15 The Fab Lab movement provides spaces for designers to experiment with new product designs using innovative manufacturing equipment.

16 R P Mudge and N R Wald, 2007, 'Laser engineered net shaping advances additive manufacturing and repair', *Welding Journal*, New York

17 Hybrid Manufacturing Technologies, 2016, 'Technology', www.hybridmanutech.com

18 Royal Academy of Engineering, 2013, *Additive manufacturing: opportunities and constraints*

19 P Reeves and D Mendis, 2015, *The current status and impact of 3D printing within the industrial sector: an analysis of six case studies*, The Intellectual Property Office

20 C Telenko and C Conner, 2012, 'A comparison of the energy efficiency of selective laser sintering and injection molding of nylon parts', *Rapid prototyping journal*

21 P Reeves and D Mendis, 2015, *The current status and impact of 3D printing within the industrial sector: an analysis of six case studies*, The Intellectual Property Office

22 P Collinson, 2 October 2014, 'Printers with refillable tanks set to revolutionise home printing', *The Guardian*

23 B Krassenstein, 2014, 'Over 50% of all homes to have 3D Printers by 2030 – market worth $70 Billion annually', *3D Print*

24 Foresight, 2013, *The future of manufacturing: a new era of opportunity and challenge for the UK, summary report*, The Government Office for Science

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