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NEW MATERIALS AND THE CIRCULAR ECONOMY

Ceci n'est pas un ananas.

EDITORIAL

Novel materials – new opportunities and new challenges for the circular economy

Environmental scientists today live and work, as the apocryphal Chinese phrase has it, in 'interesting times'. Many of us feel that our profession is addressing some of the world's largest and most intractable challenges, and that proper consideration of climate change, air pollution, water scarcity and soil erosion needs to be brought to the top of the political decision-makers' heap, nationally and internationally. Wherever we live, we are facing common global environmental risks, with problems such as contamination, sea-level rise, population pressure and poverty overlain onto the local situation.

Our specialist services as expert analysts and forecasters of the emerging situation are clearly important. However, as environmental scientists we are more frequently involved in identifying the impacts of contemporary lifestyles on the natural environment and in suggesting mitigating actions than actually developing technologies that can assist. We need to work in partnership with materials scientists, chemists, physicists and engineers to address issues of energy generation, transport, water treatment and waste disposal in practical ways.

Researchers are exploring and developing exciting new materials and industrial processes that manufacturers are bringing to market very rapidly. Substitution of traditional materials with novel ones has taken place historically in many areas of manufacturing, but the pace of change today is unparalleled. These new materials are lighter in weight, stronger and more energy efficient to produce and use, and allow new processes and reactions to take place that have previously not been possible (in renewable energy generation, for example). Their development means that the demand for some raw materials is growing exponentially – the rare earths required for wind turbines and mobile phones being a well-known example. At the same time there is a growing demand from the developing world. Both of these factors mean that in future the Earth's population will have to manage with less material per person, on average. Hence recovery and reuse of the materials or their chemical constituents is crucial.

And yet some of these novel and smarter materials pose problems when their whole life cycle is considered. On their first use they offer potential energy savings, but without ways of recovering them from mixtures of materials, or of reusing components made from them, they are likely to end up lost in landfill. This could be taking us further away from a sustainable circular economy, regardless of the energy savings.

In 2014, a conference of technology specialists and industrial users met to consider the opportunities and risks afforded by some emerging novel materials. It was brokered by a partnership between Green Alliance, the Environmental Sustainability Knowledge Transfer Network (now the Knowledge Transfer Network), the Technology Strategy Board (now Innovate UK) and the High Value Manufacturing Catapult Centre. Materials specialists, waste managers and environmental scientists identified some of the emerging trends and debated the challenges brought by novel materials. Support was provided by the UK's Research Councils and the Waste and Resources Action Plan (WRAP).

This issue of the environmental SCIENTIST brings together papers from some of the speakers at that meeting, with contributions from other industry experts. We hope that it offers a timely and stimulating read.

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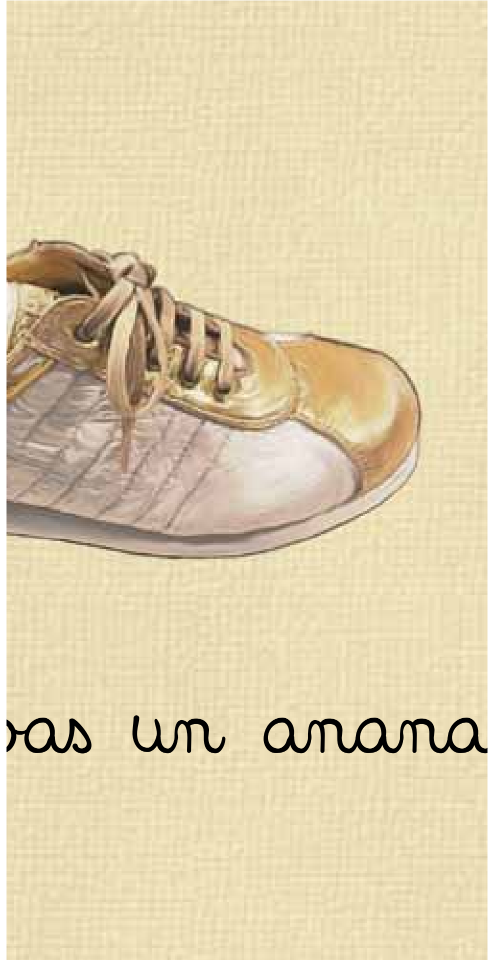
CONTENTS



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INTRODUCTION

New materials for new ways of making things

Carolyn Roberts and **Julie Hill** provide an overview of current and future developments in novel materials and the circular economy.

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If readers of the environmental SCIENTIST also read *New Scientist, Nature* or the many journals covering developments in chemical engineering, they will see an astonishing range of new materials being discussed. These are generally referred to as 'novel materials', and they include a wide variety of constituents in innumerable different formulations. Their development is part of a radical shift in society's use of chemistry, the implications of which are only starting to be investigated by environmental scientists.

The best known contemporary 'novel materials' are probably the 17 rare earth elements found in economically extractable quantity in only limited areas of the Earth's crust. These substances have unique magnetic, luminescent and electrochemical properties that make them invaluable in electronics including renewable energy generation, mobile phones, lasers and the motors that power hybrid cars. Perovskite, a calcium–titanium oxide found in igneous rocks generated close to or in the Earth's mantle and in meteorites, has similar characteristics.

There are also materials appearing that are novel formations of traditional ones, such as ceramics and glasses with exceptional strength and rigidity, or metallic substances so light that they are known as 'frozen smoke', which are astonishingly strong and affording unprecedented levels of thermal insulation. These are used increasingly in the construction industry. Multiferroic and magnetoelectric materials, as well as crystals with unique or exceptional electrical or magnetic properties similar to the piezoelectric crystals familiar from gas lighters, are other examples of novelty. Green chemistry will give us ever greater numbers of novel materials based on biotic (bio-derived) rather than abiotic (mineral) feedstocks.

A further group is the tiny manufactured particles between 1 and 100 nm in diameter known as nanoparticles, which have been used in such prosiac applications as microbe-resistant 'smell-free' socks, as well as in coatings and medicines. A related development is artificially manufactured nanotubes, increasingly used as filtration media. Nanoparticles of some elements have characteristics that may be completely different to those demonstrated when the material occurs in larger pieces: gold nanoparticles are highly reactive, for example, whereas the bulk material is famously inert.

MANAGING NOVEL MATERIALS

In 2008, the (then) Royal Commission on Environmental Pollution (RCEP), under the chairmanship of Sir John Lawton, published a report, *Novel Materials in the Environment: The case of nanotechnology*, which investigated the environmental implications of some of these emerging substances. Their concern was prompted particularly by two recurring themes. First, some increasingly used materials, such as cadmium in photovoltaic cells, are toxic to humans or corrosive and require very careful handling and disposal. Second, some novel materials, particularly nanomaterials, were at risk of being released into the natural environment with unpredictable consequences. Overlain onto the two themes were some concerns about an undue dependence of the UK economy on sources of materials that lay in areas of the world where the politics were unpredictable and the supplies therefore unreliable. There was also concern about the environmental implications of their extraction and processing.

TYPES OF NOVEL MATERIALS

The RCEP distinguished four broad types of novel materials, a classification that remains helpful today.

- Materials previously not used on an industrial scale, including some metals (such as rhodium and yttrium) and compounds derived from them, used in new ways;
- New forms of existing materials with characteristics that are significantly different from naturally

occurring forms (such as new types of colloids, the carbon-based substance graphene, and some types of nanoparticles);

- New applications of existing materials or existing technological products formulated in a new way that lead to different hazards to human or environmental health (such as fossil-fuel additives, substances used in 3D printing processes, plastic food packaging and many nanomaterials); and
- Familiar materials that may enter the environment in different forms to those envisaged in their manufacture or use (such as microscopic plastic particles used in cosmetics or those arising from the breakdown of allegedly biodegradable plastic bags).

Carbon fibre-reinforced resins ('carbon fibres') vary in their chemistry, but all are exceptionally strong for their weight. This composite of fibre and matrix is used in airplane bodies, sports equipment and protective textiles such as Kevlar. Carbon fibre is being used in car bodies.
Image © Dutourdumonde

THE FIFTH GROUP

The groups are not entirely mutually exclusive, and an increasingly important fifth group of novel composite materials might be added to these four. Composites include mixtures of different materials, often bonded at the molecular level to yield unique properties. Sometimes the materials consist of an inorganic and an organic material, bonded as sheets or layers. The paper/plastic/aluminium layers in drinks cartons are one widely used example. Synthetic rubber is an example of a hybrid composite, where mineral filler is mixed with an organic polymer. The commercial manufacture of synthetic rubber immediately before and during World War II underpinned further experiments on hybrids, and was the basis of many other more complex materials. For example, exceptionally dense thermoplastic composites can be made by including metal powders in polymers, replacing materials such as lead or tungsten in applications such as radiation shields, vibration-damping panelling and in balance-adjusting weights for tennis racquets.

THE NEW FORM OF CARBON

Graphene is a fascinating example of a novel material that has been acclaimed for its amazing strength, flexibility and electrical conductivity, with the potential to transform the electronics industry. It is estimated to be approximately 100 times as strong as steel, and can heal itself if free carbon atoms are nearby and available. Made from sheets of carbon one molecule thick, graphene was extracted from graphite using adhesive tape (a process known as exfoliation), and placed onto silicon wafers in 2004 by Nobel Prize-winning scientists Andre Geim and Konstantin Novoselov at the University of Manchester.

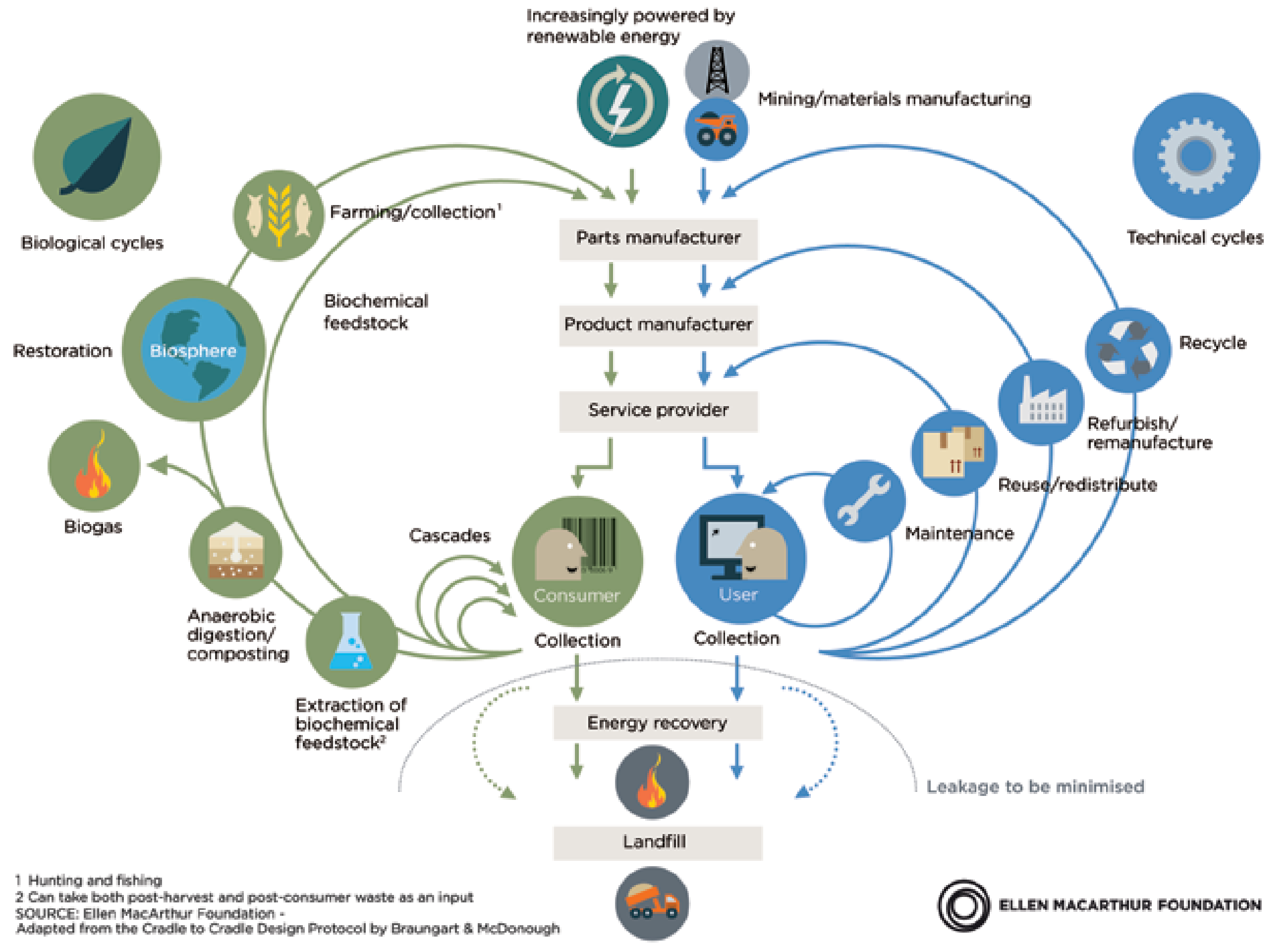
Two UK companies are already manufacturing graphene commercially and the use of graphene layers in composite materials in tablet computers, mobile phones, biomedical devices, and graphene nanotubes in water filtration equipment is escalating. Graphene also looks suitable for use as a strengthening layer between other materials such as polymers, and in 3D printers.

At present the amounts being produced are relatively small. However, there are potential challenges associated with its. Recovering graphene nanotubes from silicon-based electronic components or thin sheets of graphene oxide will be almost impossible, and adverse effects from nanoparticles of graphene have potentially been identified in surface and groundwaters in the USA. The particles are very mobile and thought to be potentially hazardous to human health, so landfilling such electronic waste is particularly undesirable.

Some novel materials imitate nature, a quality known as **biomimicry**. The delicate photonic microstructure of butterfly wings can be replicated through mineralization using metal oxides or alkoxides to produce colour changes through light interference, rather than pigmentation.
Image © als

THE DRIVERS FOR DEVELOPMENT

Despite their high cost, it is new or increased functionality, increased efficiency of some devices, and the need for substitution of toxic or hazardous materials with more



▲ **Figure 1. The circular economy - an industrial system that is restorative by design. (Courtesy of the Ellen MacArthur Foundation).**

benign substances that is driving increased use. Many of these materials are lighter in weight than those they replace, which reduces the energy consumption during their manufacture or subsequent use.

Some have allowed renewable energy to be generated for the first time, for example through photovoltaic cells and electricity from wind turbines. Nanomaterials in particular are playing an increasing role in sustainable technologies for energy conversion, storage and savings. They are appearing in solar cells, batteries and supercapacitors, fuel cells, thermoelectrics, superconductors, and more efficient lighting. Whilst the typical development time for a new product is 15 years from concept to commercial deployment, there is huge optimism about the emerging possibilities, and all of these substances are an increasingly important part of modern industrial technologies.

CIRCULAR ECONOMIES

These novel materials and processes are emerging just as the concept of the circular economy is taking hold. Circular economy takes the familiar ideas of reduce, reuse and recycle and puts them into a framework that envisions entire economies built around the principle of using resources to their maximum value, keeping them within the economy indefinitely, and aiming to 'design out' waste from the system as far as is possible (see **Figure 1**). This means keeping resources in use much longer, preferably as whole products rather than materials. Circularity can be achieved through longer-lasting products, greater repairability and upgradability, and by using sophisticated techniques of remanufacturing to return products to a state that is as good as new, or even better than new.

If products have to be split into materials for recycling (which takes energy) they should ideally be designed for this to happen quickly and easily, and without added components or chemicals that might contaminate the reusable materials. An important aspect of circular economy thinking is for manufacturers to reduce their use of physical resources by offering a service rather than a product to their customers (miles travelled rather than tyres, for example), which gives those providing the service an incentive to secure maximum value from the resources they use.

These ideas have been variously expressed as 'resource efficiency', 'industrial ecology' or 'industrial symbiosis', 'zero waste' or 'cradle to cradle', and several of the papers in this issue of the environmental SCIENTIST

▲ Figure 2. The aim to send zero waste to landfil lies at the heart of the circular economy conceptual framework (© Pn_photo)

explore them. Resource efficiency as a goal for companies and supply chains has been enshrined in EU and UK policy and practice, and it provides the foundation for circular economy thinking. Industrial ecology is a strong academic discipline providing many of the tools for understanding the circular economy, including lifecycle analysis, systems design and industrial process design; industrial symbiosis is an exemplar of this, where the waste from one manufacturing process effectively becomes the input for another process. Zero waste has been taken up as a rallying cry by governments and companies alike, starting with the idea of zero waste to landfill (our departure from this least desirable end-of-life option for society's unwanted materials being seen as the most urgent direction to take).

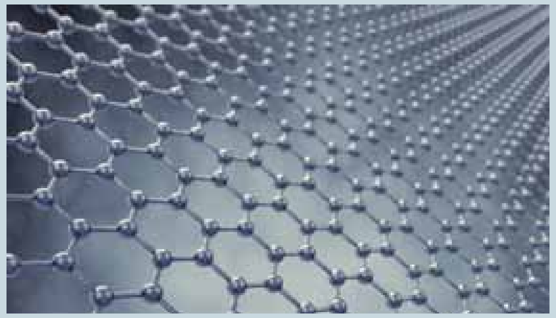
Cradle to cradle provides the purest theoretical framing of the circular economy ideas, dividing society's resources into technical (abiotic) and biological (biotic) and aiming to keep these two cycles separate and endlessly restoring themselves insofar as the laws of thermodynamics allow, through the application of strict design principles. The cradle to cradle terminology was coined by a Swiss architect, Walter Stahel, some 40 years ago, but the ideas were refined by Michael Braungart, a German chemist and former Greenpeace activist who with American architect William McDonough published *Cradle to Cradle: Remaking the way we make things* in 2002.

Fabrication from biological materials. Research at Queen Mary University of London is taking place into nanostructured solar photovoltaic cells made from the shells of shrimps and other crustaceans. Hydrothermal carbonisation of the chitin and chitosan generates carbon quantum dots, which when coated on standard zinc oxide nanorods, can replace the exotic material ruthenium.
Image © rprongjai

THE CHALLENGES OF NOVEL MATERIALS

Composite materials present some of the most interesting challenges and potential opportunities. At their most basic level, composites are mixtures of materials with different characteristics, bonded together to generate new and more beneficial properties. Composite materials fall into two groups. 'Multiple' materials are made at the millimetre to centimetre scale and have been used for millennia, whereas modern 'hybrid' materials are structured at the molecular, nano- or micro-scales. Wattle and daub (used in ancient buildings), plywood and concrete are examples of 'multiple' composites whose constituent parts can be challenging to separate, and may be mixed organic and inorganic materials. For the large volumes of concrete required by modern Western societies, any reuse usually involves crushing the stone and cement mixture and remoulding it into lower value products using additional cement. However, the addition of steel rods to create reinforced concrete creates far greater difficulties for subsequent reuse or recovery. Similarly, operating theatre surfaces and some more expensive kitchen worktops are now made of an aluminium trihydrate (ATH, derived from bauxite) and an acrylic polymer composite (Corian) that is currently impossible to separate or recycle. Reuse of the whole component is likely to be the main option here.

Some progress is being made on recycling composite materials. About 160,000 tonnes per year of flexible laminate packaging is used in pet-food pouches, drinks containers and toothpaste tubes in the UK. This thinly layered aluminium and plastic composite provides excellent protection from light, moisture and oxidation, and is much lighter to transport than the equivalent sized bottle or can. Because, like many composites, it is difficult to separate out the components, currently most of it ends up in landfill. However, UK Government-funded research is now taking place on recovery of the aluminium and conversion of the plastic to a fuel oil using microwave-induced pyrolysis at waste depots. The clean aluminium has only 28 per cent of the carbon footprint of primary metal and moreover Enval,



Graphene is a material made from a single layer of carbon, rendering it incredibly strong, light and conductive to electricity. Not yet manufactured commercially, it can be produced in the laboratory by pulling sheets of atoms from a block of graphite using adhesive tape. Potential uses include films, paints and coatings, semiconductors, lubricants, batteries, and 3D-printing material.
Image © Nobeastsofierce

the company managing the technology development for this project, have estimated that across Europe they could generate £200 million per year from its sale. This appears to make good sense in terms of a more circular economy.

Biodegradeable plastics, valuable for wrapping food, are broken down into water, carbon dioxide and organic compounds over a period of months by bacteria and fungi. Some formulations leave a microplastic particle residue, which can accumulate in aquatic environments.
Image © pongsak1

Scaling up to larger products, a great deal of research is being undertaken at the UK's National Composite Centre on the use of fibre-reinforced composites by the automotive industry. At prototype level, complete floor pans for saloon cars can be produced using automated production, baking carbon fibre mesh with polymers in giant ovens or in presses to harden the matrix. These floor pans are much lighter but equivalent in strength to metal alternatives, and hence improve the fuel efficiency of the car during its life. Thus atmospheric carbon emissions are reduced, particularly if the car uses petrol or diesel fuel.

At present, cost restricts the use of this novel material mainly to spacecraft and aircraft, high-value sports cars and military vehicles. However, carbon-fibre composites are also starting to appear in cheaper vehicles and in pipes for drinking water and sewage (where their resistance to fracturing brings benefits in reducing leakages). There has also been widespread earlier use of different types of fibre composites in boat hulls and swimming pool liners. In the case of these items, there are already challenges in recycling materials following breakages, and there has been very little research on how this fits the aspirations to a more circular economy.

3D PRINTING

The previous examples mainly illustrate novel materials that have both the capability to reduce power consumption during their lifetimes in specific products because they are exceptionally light or strong, but with the disadvantage that they may also be difficult to recycle or reuse. The graveyards of aircraft in Central Australia may grow bigger as carbon fibre replaces the recyclable steel and aluminium of most existing hulls. 3D printing is more complex again. 3D printing describes a process of additive manufacturing – producing items by progressively bonding very thin layers of product one on top of another using heat or lasers. The 'printing' is done very quickly by ink jets under robotic control. 3D printers using polymers as the raw material are now being sold for domestic or hobby use, and are increasingly being used in manufacturing prototypes.

Whilst many of the demonstrations seen today produce small toys, or tiny plastic parts, they have the capability to be used to produce both larger items (such as specialised interlocking building blocks for rapid house construction), or metallic structures (such as dental and biomedical materials, including bone replacement, by an industrial-scale process known as 'laser sintering'). A further use is in printing electronics circuits where conductive ink and non-conductive materials are fused together at nanometre scales and embedded into other objects. There are astounding aspirations to produce human organs by 3D printing using human tissue – 'bioprinting', the tissue engineering of replacement heart valves, trachaea or kidneys, for example.

New lithium compounds have improved the electrodes in laptop batteries.
Image © Thejipen

3D printing in the home or in small workshops is seen as a potential way of effecting repairs to items of equipment that have broken and would otherwise not be repairable without difficulty or expense. Design software and recipes can already be freely downloaded from the web, and used to produce one-off replacement parts for some items, extending their lives without the need to have spare parts shipped to users. It might be expected that this would militate against a throw-away society. And in the case of 3D printing of metallic objects from powdered metals, their production does not involve drilling or milling waste metal from large blocks. However, against that has to be set the increased energy demands of producing individual components by distributed as opposed to mass production, the likely emissions to atmosphere and land during the printing process, the question of the recyclability of the polymers in common use, and the short lifespans of the machines themselves. It is unclear yet whether 3D printing will offer a genuine solution to more sustainable production of manufactured products, even if it improves some aspects of the circular economy.

Aerogels are incredibly light, strong and porous materials, which can be used as thermal insulation and in semiconductors. Supercritical drying replaces a gel's liquid with gas, leaving a 'solid smoke' which is 98% void. Early examples were made from silica, but other types are based on metals, carbon or biological materials such as agar. Aerogels now appear in cars and sports equipment.
Image: NASA/JPL (http://stardust.jpl.nasa.gov/photo/aerogel.html)

MEETING THE CHALLENGES

Sir David King, former chief scientific advisor to the UK government and special representative for climate change, commented in relation to the forthcoming climate change negotiations in Paris that:

"Greener technologies, including novel materials that are lighter, stronger, more efficient and smarter than those they replace, are potentially part of the solution. However, it is imperative that we avoid taking decisions that lead us into environmentally damaging cul-de-sacs, and that the use of these materials takes account of the environmental impacts of their use during their whole lifecycle, and gives proper consideration to possible ways of recovering and reusing their constituents."

In future, the reputations of the research, manufacturing and retailing communities might rest on how well they rise to the challenges of novel materials. To take good decisions, all players in the development of these exciting new materials and processes should be talking to each other – chemists, materials specialists, environmental scientists, material recovery companies, and, crucially the users of the materials all the way through the supply chain. This is the aim of a joint project commencing April 2015 led by Green Alliance, with funding from Innovate UK, the EPSRC, the High Value Manufacturing Catapult, and with support from the KTN. Many of the people and processes featured in this special edition will be involved, with the likely outcome of well-considered developments and choices. **ES**

READING MATERIAL

Much recent development in this area remains commercially sensitive, but for good analyses of the environmental implications of some types of new materials within the last decade, see:

Vouldis, I, Millet, P, and Vallés, JL. (2008) *Novel Materials for Energy Applications: A decade of EU-funded research. European Commission Directorate-General for Research.* Office for Official Publications of the European Communities, Luxembourg. ec.europa.eu/research/industrial_technologies/pdf/novel-materials-for-energy-applications_en.pdf.

Royal Commission on Environmental Pollution (2008) *Novel Materials in the Environment: The case of nanotechnology*. Cm 7468. Office of Public Sector Information, London. www.gov.uk/government/uploads/system/uploads/attachment_data/file/228871/7468.pdf.

For an example of the environmental implications of a novel material see:

Lanphere, JD, Rogers, B, Luth, C, Bolster, H, and Walker, SL. (2014) Stability and Transport of Graphene Oxide Nanoparticles in Groundwater and Surface Water. *Environmental Engineering Science*, July 2014, pp350–359.

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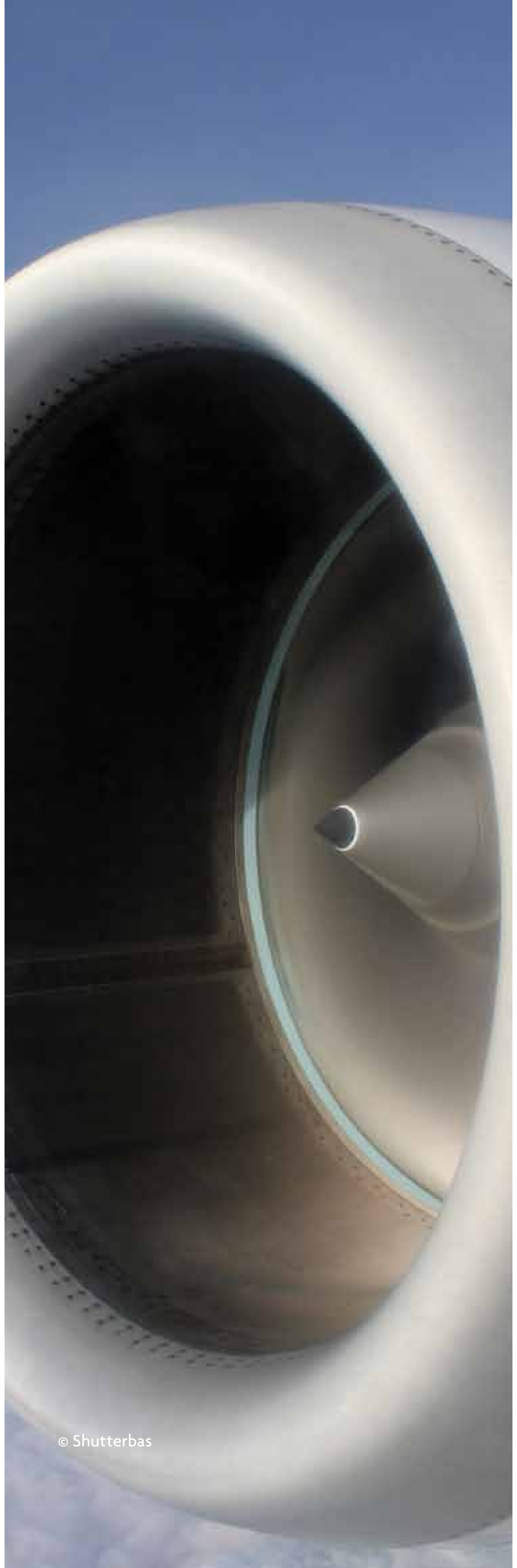
Julie Hill is Chair of the Waste and Resources Action Programme (WRAP), an Associate of Green Alliance, and an independent Board Member for the Consumer Council for Water. She is also the author of The Secret Life of Stuff: A Manual for a New Material World published by Vintage Books in 2011.

Designing novel products and materials for greater circularity

Liz Goodwin, Peter Maddox and **Patrick Mahon** show why it is so important to build a lifecycle view into product design.

A circular economy is an alternative to the traditional linear economy, which relies on making, using and throwing away products often produced using virgin materials. A circular economy model keeps resources in use for as long as possible, extracts the maximum value from them whilst in use, then recovers and regenerates products and materials at the end of each service life.

There are clear economic factors encouraging the move towards greater circularity. Business is increasingly concerned with the security of supply of the resources (such as metals, plastics or textiles) that they need for their products and services. The prices of those resources have risen and become more volatile, changing at an increasingly rapid pace due to mismatches between supply and demand. This is being driven at least in part by the expected increase in global demand – the projected increase in the global population from 6.5 billion today to 9.6 billion in 2050 – and in particular the 3 billion extra middle-class consumers expected globally by 2030[1].



RESOURCE EFFICIENCY

These concerns can be addressed by companies reducing their reliance on virgin materials, for example through greater resource productivity (getting more products or services out of the same amount of input resources) leading to increased competitiveness by enabling them to out-compete other companies that do not reduce their exposure to these risks.

In addition, research has suggested that UK businesses could save £23 billion from resource efficiency measures that would cost very little, but would improve their circularity. At a global level, McKinsey has estimated that in 2030, resource productivity improvements could be worth $2.9 trillion a year[2].

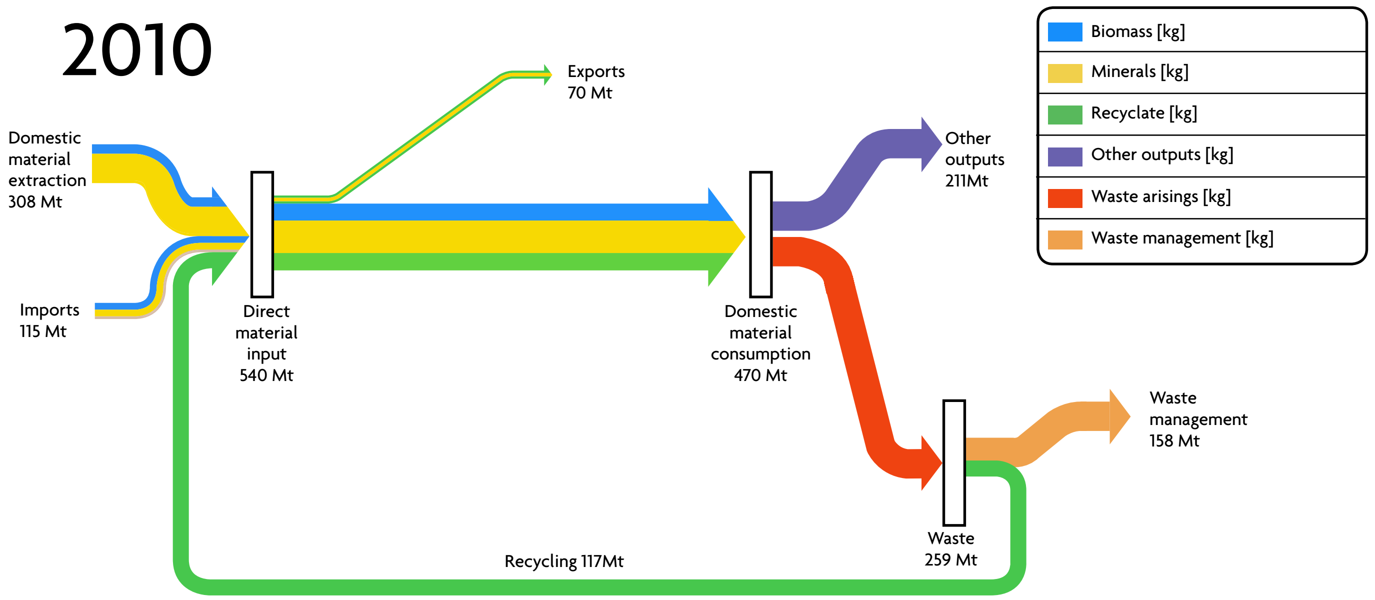
Whilst businesses have a clear economic incentive to use resources more efficiently, the move to a circular economy also generates environmental and social benefits. The environmental benefits include a reduction of the impacts of the extractive and primary industries (in terms of energy and water use, CO_2 emissions, and loss of natural capital and biodiversity). Similarly, the end-of-life impacts of waste production and management (in terms of air, water and land pollution) are avoided. Research carried out by the Waste and Resources Action Programme (WRAP) in 2009 found that if more products were reused rather than thrown out, the UK could reduce its greenhouse gas emissions by nearly four million tonnes a year over the decade to 2020[3]. Alternatively, recycling of aluminium drinks cans saves 95 per cent of the energy needed to make them from virgin materials.

The social benefits include the net creation of jobs that can help to reduce unemployment and address labour market imbalances in developed economies. For example, in the UK, new research undertaken by WRAP and the Green Alliance has estimated that 205,000 new jobs could be required by the uptake of circular activity, which could offset up to 11 per cent of future losses in skilled employment[4]. Areas where unemployment is high, such as in the North East and West Midlands, could also see the greatest impact on job creation.

HOW CIRCULAR IS THE UK ECONOMY?

As yet, there is no single agreed methodology for measuring the circularity of an economy. However, WRAP has used Sankey diagrams to show the materials entering, moving through and leaving the UK economy.

Figure 1 shows WRAP's Sankey diagram for the UK economy in 2010. It shows the flow of organic materials (biomass) and inorganic materials (minerals) into and through the economy, and the amount of waste that comes out, split into the fraction that is recyclate and the remainder, which ends up in energy production or in landfill (waste management). A rough measure of the circularity of the UK economy can be calculated as the weight of material recycled divided by the weight of domestic material consumption (DMC). In 2010 the figure was 25 per cent (117 Mt recycled/470 Mt DMC). This represents a significant increase compared to a decade earlier, when the figure was 9.5 per cent (47 Mt recycled/497 Mt DMC).



▲ **Figure 1. Sankey diagram for the UK economy in 2010. (Original source: WRAP[5]).**

WRAP'S CIRCULAR ECONOMY VISION FOR 2020

WRAP has estimated the circularity metric for 2020 if the UK incorporates the circular economy into the heart of its thinking. By taking real steps to reduce waste and reuse and recycle more, the UK could use 30 Mt less direct material input, recycle 20 Mt more material and produce 50 Mt less waste (see **Figure 2**). Under this scenario, the circularity of the UK economy would increase to 31 per cent. In addition, the changes would improve the UK's trade balance by £23 billion per year, improve business competitiveness by reducing costs by £52 billion per year and create up to 10,000 new jobs in the recycling sector[6].

THE CLOSED LOOP AND PLASTIC PACKAGING

The benefits of a circular approach to the product lifecycle can be illustrated by reference to something that is familiar to all of us: plastic packaging. **Figure 3** shows how a closed-loop approach benefits five key stakeholders across the product supply chain (the chain of companies and people involved in getting the product to the consumer and then recycling it):

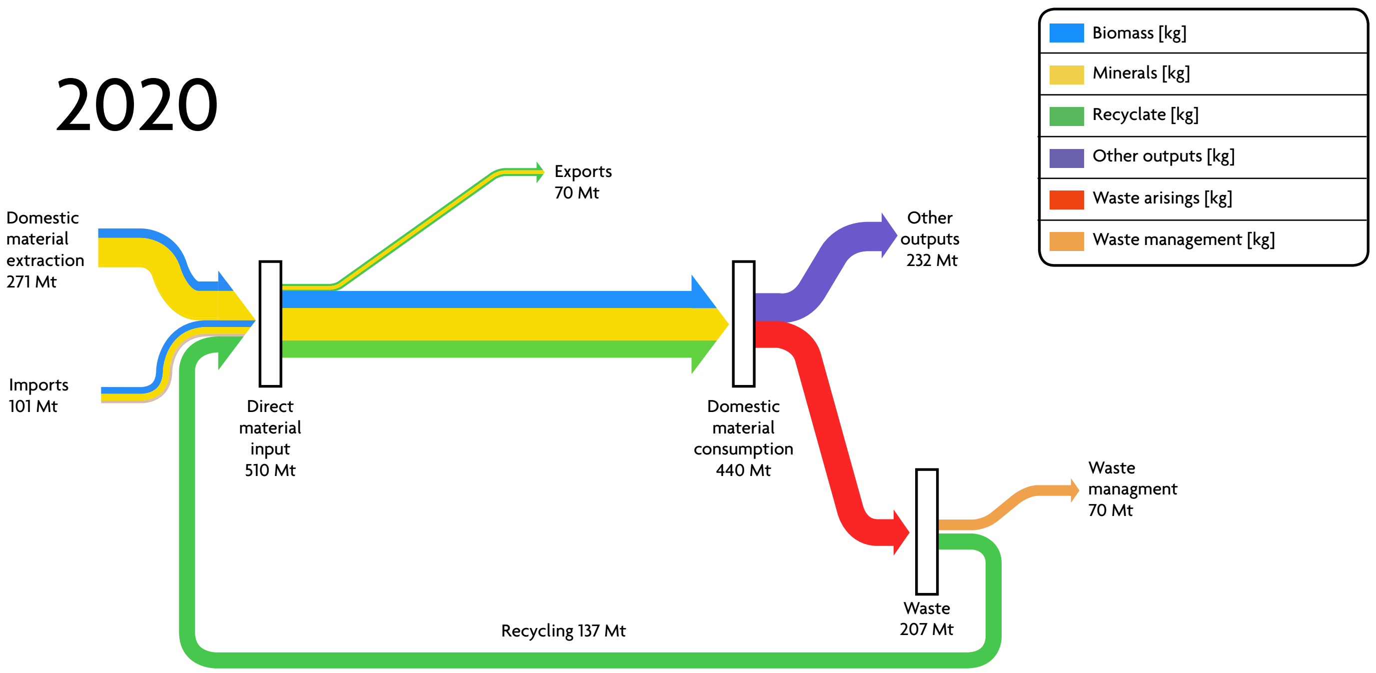
- the packaging manufacturer;
- the retailer;
- the consumer;
- the local authority that collects the post-consumer packaging waste; and
- the reprocessor that turns it back into new packaging.

Recycling involves a two-stage process, where plastic is separated from other materials, then either melted directly or shredded and melted down before being processed into granulates that can be used again. This has a number of benefits (conserving non-renewable fossil fuels, reducing energy consumption, reducing waste going to landfill and reducing carbon and other emissions) compared to landfilling or incinerating the waste plastic, and making a new plastic product from virgin materials.

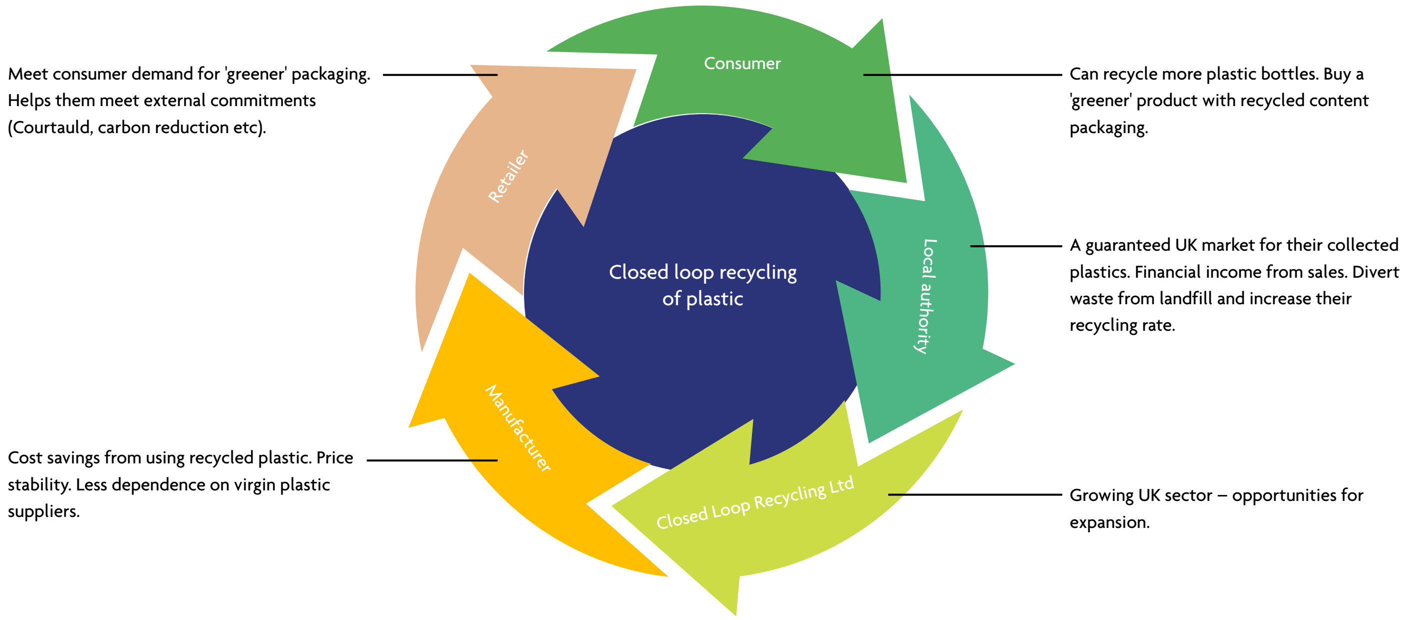
CRITICAL SUCCESS FACTORS

WRAP's experience would suggest that several factors are critical to the success of building circularity and closed loops into new products and materials. Initially these will include taking a supply chain approach from the start, understanding the market and identifying where there are opportunities to 'close the loop'. This could be about eliminating surplus waste from the start, designing products with repairability in mind, or reusing and recycling products once they have been used. Businesses need to identify which segments of their operations are most amenable to a closed-loop approach, and build the capacity in those segments.

Once a potential closed-loop product has been identified, it may then be necessary to undertake product development trials, both at a demonstration scale and then at a commercial scale, and to simultaneously develop the supply side of the closed loop (i.e. develop



▲ **Figure 2. Sankey diagram for the UK economy in 2020. (Original source: WRAP[5]).**



▲ **Figure 3. The closed-loop philosophy for plastic packaging. (Original source: WRAP).**

the sources of the recycled materials that will displace virgin raw materials as the inputs to the manufacturing process), focusing on the cost and quality of the recycled materials and ensuring that these are communicated properly to the potential customers so that they can see that a closed-loop approach will benefit them.

Two additional factors can also be important. One of the historical issues that has prevented some organisations from closing the loop as described above is a lack of price transparency in the recycled materials markets (i.e. it can be difficult for buyers and sellers of recycled materials to find out the current market price of commonly traded recycled materials). Finding ways to clearly communicate prices, through the trade press for example, can reduce this particular market barrier.

In addition, it can be difficult to attract bank finance for projects in new areas of closed-loop recycling due to the lack of pre-existing successful case studies. One solution to this can be to derisk the initial investments in a new area by providing a bridging loan from public funds, recognising that if the other critical success factors have been addressed, the project risk is likely to be lower than is estimated by commercial banks unfamiliar with the area. For example, the Closed Loop Recycling plant in London was the first in Europe to develop a closed-loop process for recycling plastic milk bottles back into plastic milk bottles. WRAP worked with them to develop the technology, and provided a loan to help build the first commercial-scale plant.

NEW BUSINESS MODELS FOR TRADITIONAL MATERIALS, PRODUCTS AND SERVICES

Many of today's products and services are designed and manufactured in ways that assume the ready availability of resources such as oil, metals and cotton. However, it is perfectly possible to take a different approach. New, more resource-efficient business models, which recognise resource constraints and are based on a closed-loop philosophy, can increase the value that can be obtained by both producer and consumer. Examples include:

- Product service systems (e.g. Rolls-Royce – 'power by the hour');
- Dematerialised services (e.g. Netflix – on-demand films);
- Hire and leasing (e.g. Forbes Rentals – renting of televisions, power tools etc.);
- Collaborative consumption (e.g. StreetBank – community sharing);
- Incentivised return and re-use (e.g. Amazon – trade-in of books and games);
- Asset management (e.g. Electroversal – refurbishment of electrical office equipment); and
- Longer lifetimes (e.g. Miele – who design longer lifetime electrical equipment).

WRAP is leading an EU-funded project called REBus (Resource Efficient Business Models), which aims to demonstrate how businesses and their supply chains can implement resource-efficient business models. The project will focus on four key markets: electrical and electronic products, clothing, furniture and construction products, as these sectors have the greatest potential to become more circular and make commercial gains in doing so.

NOVEL MATERIALS

Based on WRAP's previous experience, there are six key issues to consider when designing closed-loop systems for any new material and product system, including those based on the use of novel materials.

1. It is vital that lifecycle analysis or hotspot analysis (an alternative to full lifecycle analysis, which looks across an organisation or sector's entire product range to identify those products or materials that make the largest contribution to the organisation or sector's overall environmental impacts) is used to understand the key lifecycle impacts of the product or service.

2. A closed-loop approach needs to be built into the design of the product or service from the start, recognising that this requires consideration of the entire supply chain, not just one segment of it, so that products can be designed to be durable, repaired with ease, disassembled and recycled from the outset.

3. Strategic analysis of the product or service should be based around a future scenario where resources are tightly constrained, to identify where the largest differences from the *status quo* will occur.

4. In the context of that future scenario, consideration of the types of resource-efficient business model that might best fit the product or service is required.

5. Consideration of the approach to the design of the product (e.g. design for remanufacturing or disassembly, use of modular components) and analysis of the implications for the choice of materials is necessary.

6. The implications for the manufacturing process, as well as for the end-of-life stage of the product or service, needs consideration.

An approach that considers all of these issues from the perspective of lifecycle impacts, resource use and circularity is more likely to lead to closed-loop solutions that enable the advantages of novel materials to be used without creating future problems at end of life. **ES**

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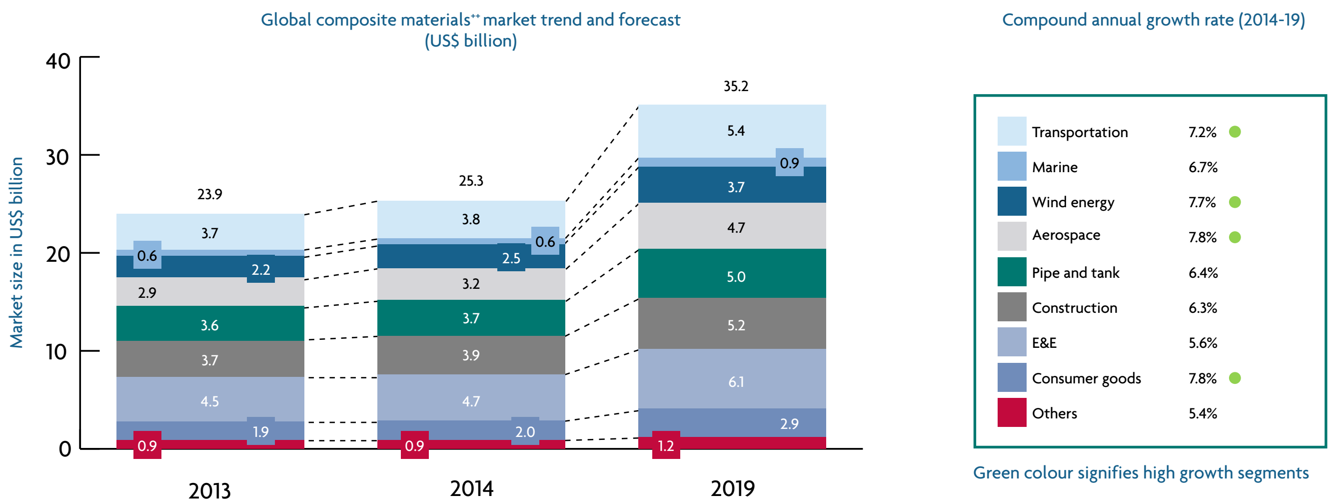
Recycling and the circular economy for composites

Stella Job assesses the options for and realities of recycling composite materials.

Fibre-reinforced polymer composites have been described as "intractable by design"[1] when it comes to recycling. But their increasing use in products as diverse as aircraft and subsea protection structures, racing cars and industrial roofing, wind turbine blades and shower trays is testimony to the fact that the same intractability is exactly what makes them stiff, strong, durable and corrosion resistant, and those properties are realised with significant weight reductions compared to traditional materials. The growth of composites in different sectors is illustrated in **Figure 1**.

The term 'composite' can be used when two or more constituents are combined to produce a material with characteristics different from the individual components. This discussion is concerned with fibre-reinforced polymer (FRP) composites (rather than, for example, composite laminates for fruit juice cartons). Most FRPs use a thermoset polymer matrix combined with glass, carbon or other fibres. Thermoplastic polymers will melt and so can be remoulded. Thermoset polymers cross-link when they set, which gives them durability and optimum strength-to-weight ratios in demanding



++NB: Composite materials market calculated as the value of key raw materials including : thermoset and thermoplastic resins, carbon fibers, glass fibers, fillers, additives and core materials, but excluding 'intermediate' materials such as: compounds, textiles, and prepregs.

▲ **Figure 1. Global composite raw materials market growth to 2019. (Courtesy of Lucintel LLC).**

TECHNICAL

applications. However, this means that they will not melt so are more difficult to recycle.

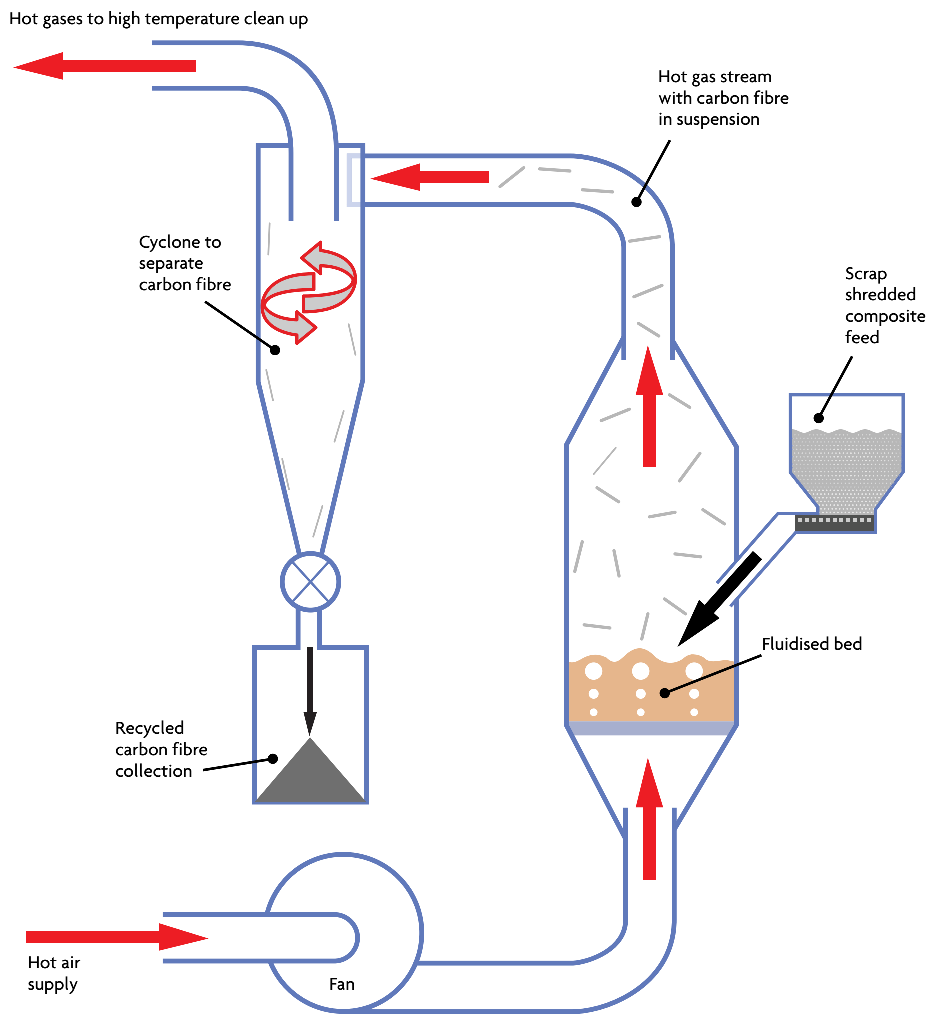
Carbon and glass fibres are energy intensive to produce, especially carbon fibre. Estimates of embodied energy for carbon fibre are 183–286 MJ/kg and for glass fibre 13–32 MJ/kg. The most common polymers used in composites are unsaturated polyester (63–78 MJ/kg) and epoxy (76–80 MJ/kg)[2]. Thus it is important not to waste the embodied energy of these materials.

No reliable data are available for composite waste volumes in the UK, but it is estimated that glass-reinforced polymer (GRP) waste from manufacturing may be around 15,000 tonnes a year, with perhaps a further 50,000 tonnes of end-of-life waste. Carbon-fibre-reinforced polymer (CFRP) waste from manufacturing could be 1,000–2,000 tonnes a year in UK, but end-of-life waste remains small. With current growth rates in manufacturing, we could expect GRP waste to increase by around two-and-a-half times and CFRP waste by three times by 2030. This is significant in itself, though small in the context of total UK plastics waste – up to 4.3 million tonnes a year[3].

COMPOSITE RECYCLING

Several processes have been developed for recycling thermoset composites. These include:

- Mechanical grinding: either to fine powder for filler, or enough to maintain some fibre length and separate out the fibres.
- Pyrolysis: the polymer is decomposed/burnt off in an oxygen-free (or limited-oxygen) atmosphere, leaving clean fibres.
- Fluidised bed: the composite is fed into a bed of sand, fluidised with a stream of hot air. The polymer decomposes, releasing the fibres and filler. These are carried out in the gas stream and collected (see **Figure 2**).



▲ **Figure 2. Fluidised bed process. (Courtesy of Professor Steve Pickering, University of Nottingham).**

- Solvolysis or other chemical processes: to dissolve off/break down the polymer and release the fibres.
- Cement kiln: GRP is fed into the kiln, the polymer is burnt for energy and the glass fibres (aluminosilicate) and calcium carbonate filler become feedstock for cement. (This process is not relevant to carbon-fibre composites as they have no mineral content for cement feedstock. However, they can be incinerated for their calorific value.).

Some very useful work is ongoing at the University of Manchester in the EXHUME project to determine the environmental impact of different recycling processes. One study estimates energy requirements for mechanical grinding of carbon fibre to be 0.27 MJ/kg when processed at 150 kg/hr using commercial equipment[4]. Thus mechanical recycling has very low energy use and virtually no emissions to the environment, as long as the residual powder is used as filler rather than sent to landfill.

Further work at Manchester (as yet unpublished) shows that mechanical recycling has a much lower impact than thermochemical processes. This is confirmed by a European project, EURECOMP, which looked at solvolysis as a recycling route. A thorough life-cycle assessment was done that "reveals that the solvolysis process is not yet competitive with treatments like mechanical recycling or energy recovery, but can possibly be competitive with pyrolysis in terms of environmental impacts."[5] This is particularly because of the energy consumption linked to the solvolysis reaction and the solvent required for washing. The life-cycle impact for pyrolysis would vary depending on the energy source used to power the process and whether the decomposed organic polymer is burned off, burned off with energy reclamation, or reclaimed for chemical value.

While environmental impact is of vital importance, in reality consideration of this has little impact on the commercial success of a recycling process, except in that where energy use is high, running costs will also be high. It is the economic viability of the process that determines its success, though that may be influenced by legislation.

USING THE RECYCLATE

In the case of the cement kiln route, or grinding to fine powder, the recyclate value is very low – it is comparable to calcium carbonate, which is plentiful and cheap. Except for the cement kiln route, all these processes will typically produce short fibres. These have inherently lower value compared to the continuous fibres produced by virgin-fibre manufacture. The value can be raised by incorporating them into semi-finished products such as veils (random or aligned fabrics) or preforms (where short fibres are sprayed into 3D shapes to be infused with polymer). These processes add cost and use energy.

Short recycled fibres can compete with virgin fibres that are sold as short-chopped or milled fibre, most notably for use in injection-moulded thermoplastics (see **Figure 3**). However, changes to the surface and handling characteristics in the recycling process mean that this is not a direct replacement.

The properties of recycled fibres have been tested in numerous research projects. In almost all cases the stiffness of the fibres is retained, but the tensile strength decreases. With pyrolysis for carbon fibre, the process can be tuned to retain almost 100 per cent of virgin fibre strength, but in reality the fibres tend to be 'overcooked' to ensure complete removal of the polymer, resulting in reductions in tensile strength down to as little as 15 per cent[6].

▲ **Figure 3. Injection-moulded under-floor vent from Hambleside Danelaw using ground GRP recyclate and in-house PP waste. (© Stella Job).**

Thermal or chemical processes will remove the size – a coating that is put on the fibres at manufacture to improve handling and adhesion to the polymer. This is not a problem for carbon fibres, though they may need to be resized to gain optimum properties in a new composite, but for glass fibres their strength and handling properties are severely compromised. So recycling of glass fibres is realistically limited to mechanical processes, unless post-treatment can recover the fibre properties. Researchers at Strathclyde University have developed a method to chemically etch and re-size thermally reclaimed glass fibres[7] and are now seeking to commercialise this.

The organic polymer part of the composite can be incinerated for energy recovery, or in the case of mechanical grinding, can be used as filler once the more valuable fibres have been extracted. Pyrolysis and solvolysis technically can allow for recovery of polymer chemicals. Numerous research projects have sought to extract and reuse the chemicals but none of these appears to be close to commercialisation as yet[8], though work is ongoing. Reuse of chemicals, probably in lower-value applications, is possible but the provenance of the recyclate would have to be carefully controlled to achieve this. Energy recovery may be a more economic option, particularly with end-of-life material.

▲ **Figure 4. Recycled carbon fibres after pyrolysis. (© ELG Carbon Fibre)**

IS COMMERCIALISATION POSSIBLE?

While fully closed-loop recycling of FRPs is not possible, a great deal of work has been done and is ongoing to optimise the value of both manufacturing and end-of-life waste. This requires commercial success, which depends on several factors.

Are the recycling technologies 'right' for commercialisation? With a few, short-lived exceptions, the only processes that have been commercialised are pyrolysis-based processes for CFRP (see **Figure 4**) and mechanical grinding for GRP, as well as the cement kiln route and energy reclamation. Grinding GRP to fine filler has been shown to be uneconomical, but there has been some success where fibre length is retained.

The recycling processes themselves are only a part of the battle. Development of products from the recyclate and markets for those products are critical and are an ongoing challenge. In many cases established regulatory standards can be a barrier to the use of recycled materials, as is the case with all recycling technologies. Overcoming conservatism is also a problem, as with all innovation. As recycled carbon and glass fibres are different in handling and surface properties from virgin fibres, processes need to be adapted to suit.

So while several processes for recycling and for creating products with recyclate have been well demonstrated, the industry is far from mature in terms of clearly defined markets. The economics even for carbon fibre are challenging, particularly in the early stages of setting up the process, developing a waste collection supply chain and finding markets for recyclate. For glass fibre, which has about one-tenth the value of carbon fibre, it is unlikely to be possible to commercialise a recycling route that does not charge a gate fee for taking waste.

The most obvious legislative driver for recycling composites is landfill tax, which contributes to the increasing cost of landfill. This certainly helps the business case for recycling – it motivates companies to segregate their waste and seek recycling routes.

Market perceptions of recycling vary considerably, with some happy to pay for their waste to be recycled while others expect to sell their waste if it is to be recycled. Many are pragmatic, and will pay if the cost is sufficiently less than landfill for it to be worth sorting the waste. However, the introduction of competition in the market can quickly change such perceptions, so there is significant risk in a business plan that depends on taking a substantial gate fee.

Likewise the market pull for recycled content varies. There is a drive for increased recycled content in construction and automotive sectors, though little willingness to pay more for it. Sectors such as aerospace are highly performance driven so may prefer to downcycle their manufacturing waste into other sectors.

WASTE REDUCTION

Of course the first 'R' is to reduce, and reducing waste in manufacturing processes is essential. Traditional manufacture with carbon fibre prepreg (fabric pre-impregnated with polymer) relies on cutting out the plies (layers) of fabric, as you would cut out pattern pieces in dressmaking, and results in very high wastage (40–50 per cent). Nesting software has reduced this a

TECHNICAL

▲ **Figure 5. Inspection of automated fibre placement (AFP) of carbon fibre on the rear-wing spar of an Airbus A350 XWB. (© GKN Aerospace).**

little, but the increased use of automated fibre placement (AFP) and tape-laying will have a far bigger effect. GKN now manufacture the Airbus A350 XWB wing spars using AFP[9] (see **Figure 5**).

SUCCESSFUL SUPPLY CHAINS

The final question is whether successful recycling supply chains will be achieved by market forces alone (with the influence of legislation). For carbon fibre it has been a real struggle despite some support from large aircraft manufacturers. We can now say that a CFRP recycling supply chain exists and there are around five companies globally (with one in the UK) recycling CFRP. This supply chain is not mature, is far from having sufficient capacity for projected volumes and needs to develop more markets for recyclate.

For GRP it has been a greater challenge[10] due to the lower value of the material and the absence of large, well-funded companies (as are found in aerospace) to support. There is a need for substantial funding and strong industry support to develop markets for GRP recyclate and to create a recycling supply chain that engages waste producers and users of the recyclate. While a landfill ban might accelerate this, it would also be a huge burden on the many small manufacturing companies.

In summary, it is clear that FRP composites are both energy intensive to manufacture and difficult to recycle. Yet their impact when the whole life cycle is considered is, in many cases, very positive. What makes them difficult to recycle is the same thing that makes them so strong, stiff and durable, and hence have good strength-to-weight ratio. We are working hard to make them as 'circular' as possible, but in the meantime their use can reduce environmental impact by halving the structural weight of a vehicle or doubling the life of a construction product.

The UK trade association, Composites UK, will continue to make it a priority to support initiatives towards effective commercial recycling and understanding and optimising the whole-life environmental impact of composites. ES

Stella Job is Supply Chain and Environment Officer for Composites UK. She began her career in civil engineering and worked for the Knowledge Transfer Network for six years. Her role involves promoting and improving the sustainability of composite materials and mapping the UK composites supply chain.

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Resource efficiency strategies and closed loops for manufacturing processes and materials

Graham Hillier, Richard Court, Julie Hill and **Carolyn Roberts** review the ways that industry can increase their resource efficiency.

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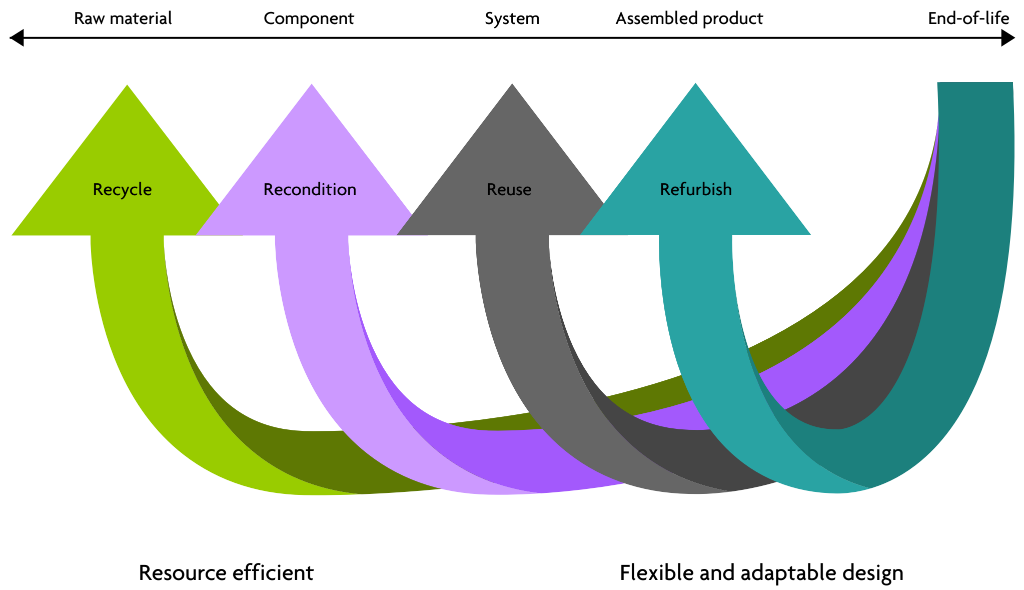


▲ **Figure 1. Schematic diagram showing a stylised manufacturing process and the options for resource-efficient reuse and recycling. (Source: Centre for REMS).**

The Centre for Resource Efficient Manufacturing Systems (REMS) is a collaborative partnership between Teesside University, the Institute for Manufacturing at Cambridge University and the Centre for Process Innovation (CPI). It was created to perform new research and to provide expertise in devising systems-level solutions for manufacturing industries that recognise the need for more sustainable operations and that can use improvements in resource efficiency as a means of achieving this. CPI itself is a specialist national innovation centre. It creates collaborative partnerships between government, industry and academia to deliver innovation that makes manufacturing processes more efficient and effective.

Amongst the core challenges are the systems underpinning the design, development and manufacturing of contemporary products that people want, or need. Items such as smart phones, machine tools or even a sports shirt are often exceptionally complex. Novel materials, new manufacturing processes and dramatic shifts in the way things are assembled and distributed are coming together to deliver these ever-more complex products and this makes tracking their environmental impact a huge challenge.

In recent years there has been an increasing emphasis on 'closed-loop' systems in manufacturing, where products or their components are no longer just recycled. **Figure 1** shows how these systems could ideally work, with loops of different kinds ensuring the maximum recovery of products, components (or parts) and materials when their first useful life is complete. This closed-loop approach reduces the need for primary resources such as minerals, metals and fuels, and consequently minimises the environmental footprint of production.

OUR UNDERSTANDING OF MANUFACTURE AND DESIGN

If they are to achieve the maximum amount of recovery and reuse, manufacturers need to understand much more about each step of their manufacturing processes and supply chains. This is so that they can seek ways of improving them to simultaneously reduce complexity, resource consumption and cost. **Figure 2** shows how raw materials or components are converted into products using resources such as people's effort, utilities (heat, power, water, transport, etc.) and capital (tied up in equipment or premises, for example). Many processes are used, by-products are produced, and emissions are made to air, water and land.

All manufacturers constantly seek ways to improve their products and processes, but in practice there are a limited number of ways that process efficiency and resource efficiency can be improved:

Continuous improvement. The classic approach is to continuously improve every step in the existing process to improve quality, speed, yield or margin. These incremental improvements bring benefits in factors such as logistics or material use.

Debottlenecking. The next step is to debottleneck existing processes by replacing one or more steps with more efficient equipment or processes. Examples include using the latest technologies such as rapid computer numerical control (CNC) machining centres and replacing human labour with robotics.

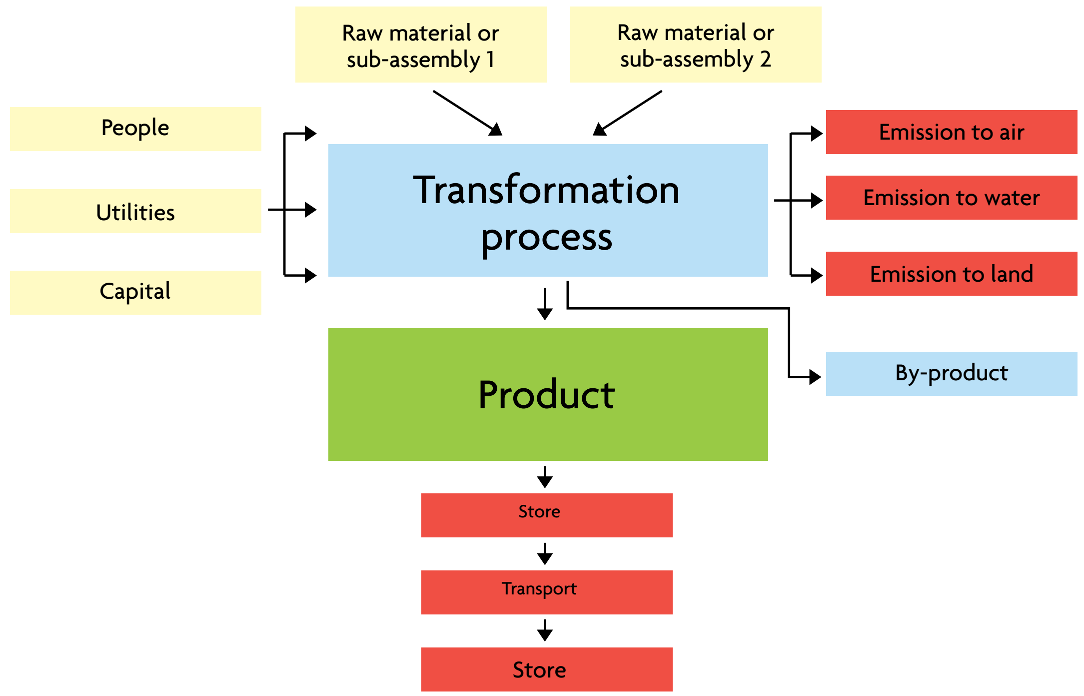
Another approach would redesign processes to eliminate some of the manufacturing steps altogether; an example is the conversion of batch production of a chemical to continuous production. This can increase the flexibility of the manufacturing process: products can be made to meet specific customer needs rather than making large numbers of identical components for stock. This allows manufacturers to produce products that meet customer needs rather than the needs of the manufacturing process.

Sustainable feedstocks. The next approach is to manufacture existing products more sustainably, for example by using renewable or biosourced feedstocks rather than fossil-based feedstocks. In some cases locally arising waste material can be used as a fuel or feedstock in a single factory. Where possible industries also collaborate to improve efficiency, using waste heat from one process to supply heat to local communities.

There is also a trend in the process industry to move to biofeedstocks where possible, as these have the potential to reduce environmental impact compared with fossil-based feedstocks.

Radical process change. The final manufacturing improvement approach is to adopt disruptive technologies that can radically change the way a product is made or the way an effect is delivered. An example is the printing of electronics, rather than the assembly and soldering of different electronic components on a circuit board. Another example is the full implementation of 3D printing, also called 'additive manufacturing', where individual parts or products can be created locally from downloaded electronic templates, using domestic-scale injection of molten plastics, or lasers and metals on an industrial scale.

Even more radical is using a discontinuous change to address problems. One such example is the potential to use light instead of medicines to treat disease – healthcare photonics. This has recently been achieved by a company called PolyPhotonix, which uses printed lights to treat diabetic retinopathy in place of injected drugs or laser intervention.



▲ **Figure 2. High-level generalised schematic diagram showing the main inputs and outputs of a manufacturing process. Processes could convert raw materials to components but could equally apply to the assembly of components into sub-assemblies (items that are used to make final products, e.g. spark plugs in engines) or products. (Source: Centre for REMS).**

New business models. The final overall improvement is to look at the way products or services are delivered to customers and changing the business model. There are increasing moves to 'servicise' some products – selling the service that the product provides rather than an actual product itself. An example is the 'power by the hour' model that companies such as Rolls-Royce now employ, where the airline pays to use the engine rather than to own it.

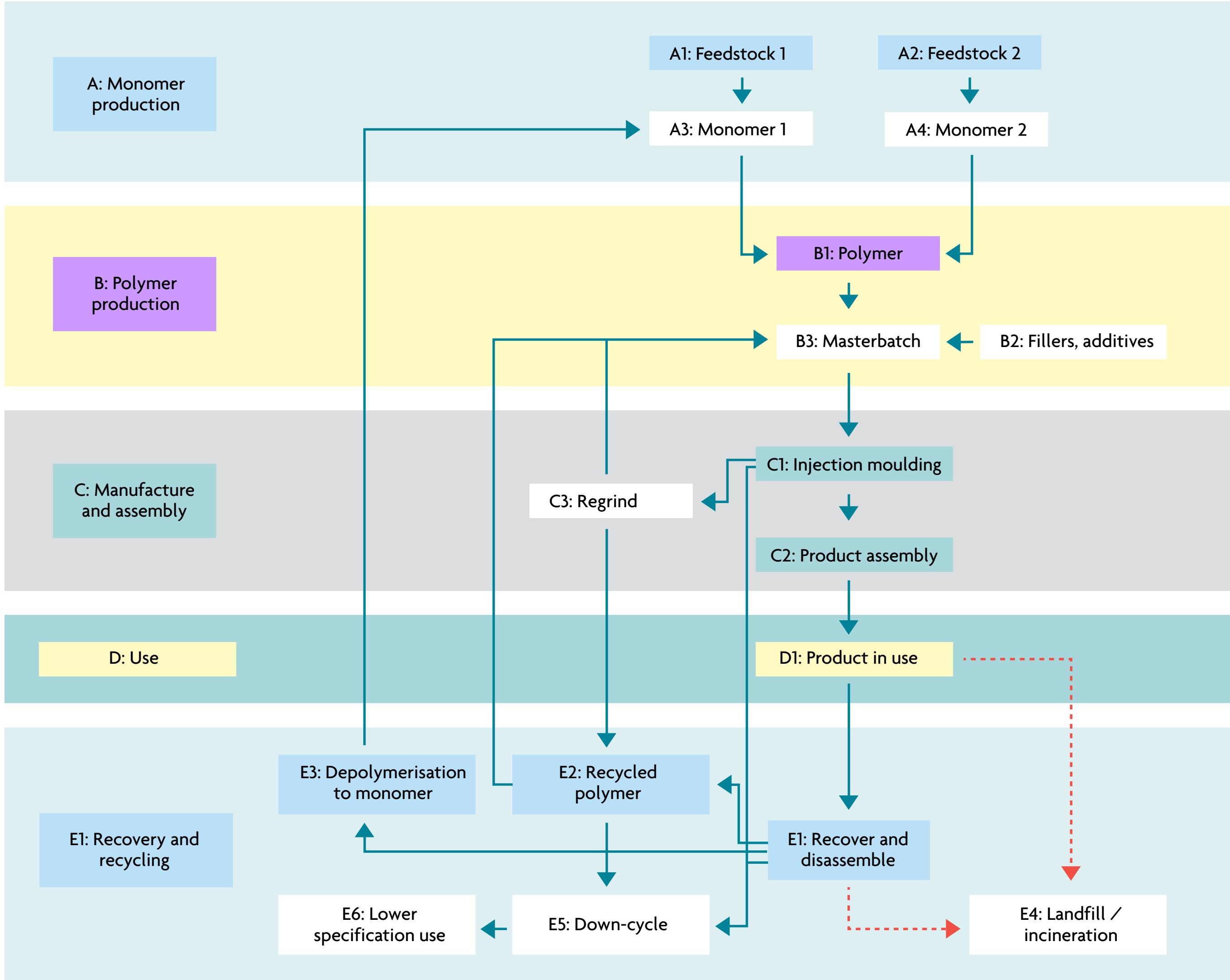
Similarly, some companies now sell light rather than light bulbs and lamp posts. This delivery of light to a street incentivises the supplier to do so as efficiently and effectively as possible, as it is paid to provide light rather than the capital equipment (lamp posts and bulbs). It is therefore attractive to the supplier to invest in high-quality products that do not require frequent replacement or maintenance, that use the minimum energy to run, and that can be reused or repaired easily.

By doing this, the providers not only reduce their own costs, but can also recycle or remanufacture items more easily at the end of their first life. This is a strong drive to technological innovation, and potentially reduces some of the environmentally damaging by-products. The reduction of resources used in the manufacture of products must nevertheless be weighed against the decreased cost and the increased demand for a product that may follow; increases in air travel are a thought-provoking case in point.

Some of the complex changes in the manufacturing systems that make and deliver products to market are so significant that they extend across many steps in the supply chain. This means that they are almost beyond the capabilities of individual manufacturing companies to implement. They need collaboration across supply chains, and may need focused efforts over a number of years to deliver the potential resource-efficiency benefits. Public-sector involvement is sometimes necessary to enable these collaborations. As a consequence the UK government agency Innovate UK provides some strategic input and funding to enable innovation to happen, steered by the Department of Business, Innovation and Skills (BIS). Targeted public investment can in principle act as a catalyst to change by allowing the early adopters to manage the business and financial risk associated with developing new manufacturing technologies.

Summarising, if we are to adopt a more resource-efficient and circular approach to our economy, the manufacturing sector needs encouragement and support to:

- Develop more sustainable processes;
- Create more flexible processes;
- Improve the efficiency of processes;
- Look at the efficiency of integrated systems;
- Use resources more efficiently;
- Convert wastes to products;
- Make better use of biological products and systems;
- Develop systems that mimic innately more efficient processes that have evolved naturally (biomimicry); and
- Convert batch processes to continuous ones.



▲ **Figure 3. Schematic diagram showing the main stages in the primary flow from raw material to product for polymer products along with the various end-of-life, reuse and recycling options that create closed loops and increase resource efficiency. (Source: Centre for REMS).**

STRATEGIES FOR RESOURCE EFFICIENCY AND CLOSED LOOP

In this section we look at approaches to the development and implementation of more resource-efficient processes or those that can operate in closed loops, where materials can be recovered and returned to their original form in low-energy processes.

We are all familiar with the plastics that are ubiquitous in our everyday lives. These polymers are used in applications as diverse as food packaging, aircraft components and clothing. However, current processes tend to focus on single use for these materials, followed by disposal or downcycling into lower-grade applications. Only a very small proportion of polymers are recovered, recycled or reused. A recent estimate by the Waste Resources Action Programme (WRAP) puts the figure at 12.5 per cent for the UK, calculated from the 4 million tonnes of plastic being processed per year, of which only 0.5 million tonnes are available as recycled polymer.

A recently developed plastic has the potential to change this, as it has many characteristics that offer the advantages of the circular economy. This is polylactic acid (PLA), which can be made from wastes (such as black liquor from the pulp and paper industry) or from biomass (such as cornstarch, tapioca or sugarcane).

Despite not being made from the fossil hydrocarbons that form the raw material of the vast majority of today's plastics, PLA uses the same processing routes, which means that existing technology can be used in its manufacture. PLA has similar properties to fossil-based plastics, with the added advantage that it

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can also be depolymerised back to reusable monomer using low-energy processes.

Figure 3 summarises the steps to produce, use and recover polymers by splitting the end-to-end lifecycle process into five main sections. This diagram shows, at a very high level, the linkages between the various life-cycle stages. Even in this highly simplified form the system is complex. Decisions are made on which of the various recovery, recycling and disposal routes are used based on the economics of the various options that are available. In some cases public-sector-funded incentives are used to encourage one or more processes. If it is technically and economically feasible, there are considerable benefits associated with the loop that involves depolymerisation (E3) to original monomers as the degradation that occurs in other recycling processes is avoided. If 50 per cent of the polymer can be recovered and depolymerised to useable monomer at the end of its useful life, this closed loop means a reduction of at least a third in the virgin feedstock required. This in turn would bring a concomitant reduction in carbon emissions, biomass production, fossil feedstock consumption and emissions to air, land and water.

Another example of a manufacturing process that has the potential to significantly improve resource efficiency is the conversion of batch processes into continuous processes. The Corning© Advanced Flow™ reactor (see **Figure 5**) is an example of one such system. Companies can use it to develop improved process reactions for a wide range of chemicals, from active pharmaceutical ingredients to resin components. The plant is compact, adaptable and scalable. Where applicable, it can reduce manufacturing costs while increasing product consistency. Reactors like this can increase resource efficiency by reducing energy and feedstock use during production by up to 60 per cent, all emissions by up to 60 per cent, and capital costs by up to 50 per cent when compared to conventional batch reactors.

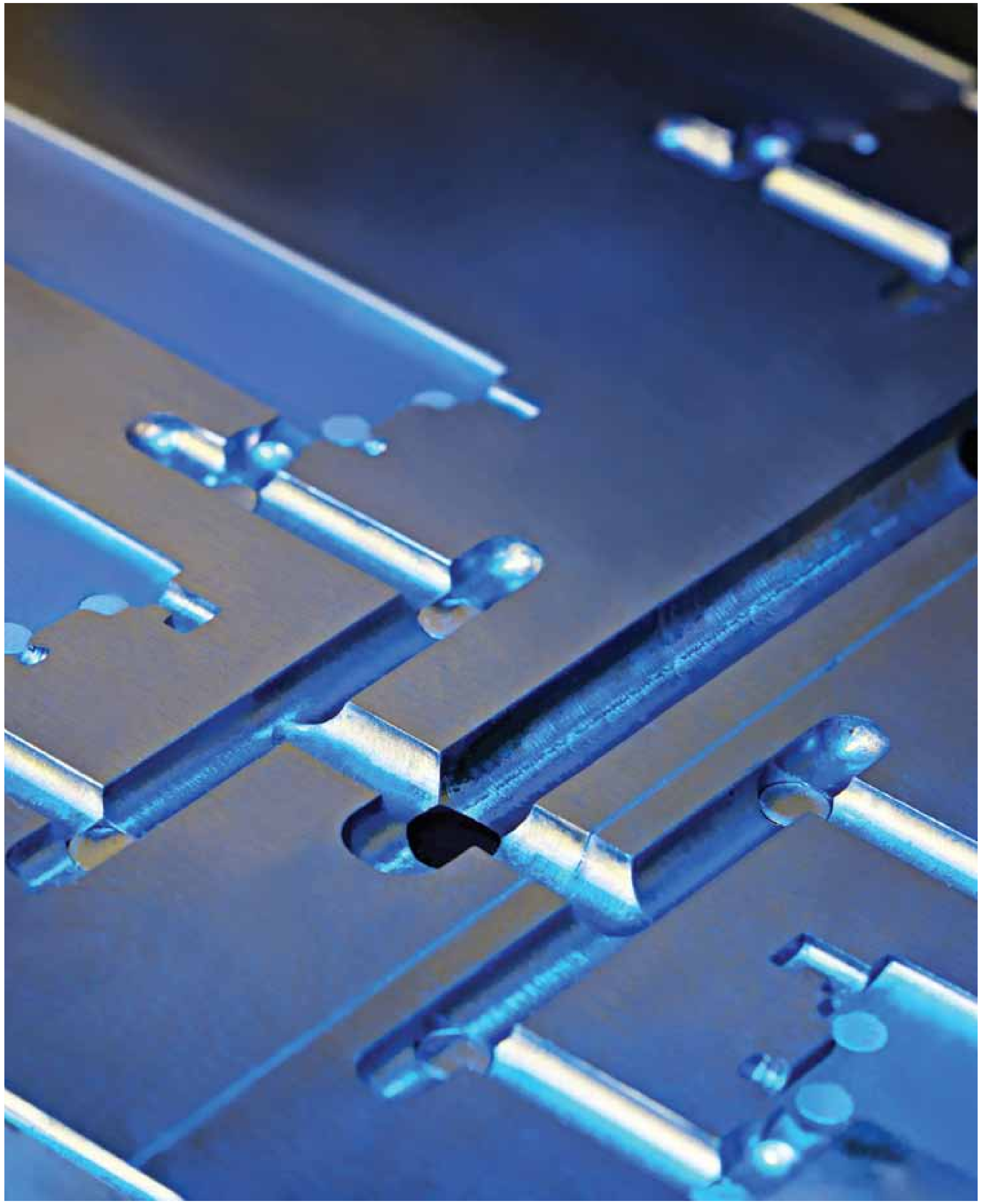
MATERIALS CHALLENGES FOR THE FUTURE

In this article a wide-ranging high-level view of some of the opportunities in the circular economy or more resource-efficient manufacturing have been discussed and examples have been given for how these may improve quality of life. However if we are to realise these benefits we will need to start thinking differently about how we design and manufacture products in the future. To realise the potential benefits some of the key materials challenges and themes for the future are to:

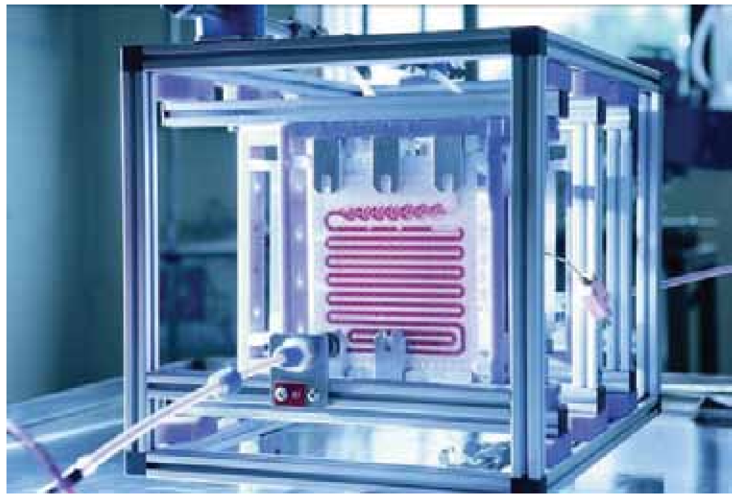
1. Reduce the number of process steps. This can be achieved by reducing the number of machining steps, which also reduces the waste from each step. It can also be achieved by technologies that produce the right shape immediately, such as injection moulding (**Figure 4**), casting, hot pressing and 3D printing, as opposed to casting metal pieces that subsequently have to be drilled and milled to produce the required shape.

2. Design resource efficiency into the product. This means designing things that can be disassembled, tested and re-used, and also things that combine form and function. This is classically referred to as remanufacturing. An example is Caterpillar's remanufacturing business that takes back, rebuilds and rewarrants power plants.

3. Make highly resource efficient flexible manufacturing processes with low capital and operating costs, and few emissions. As these processes have high yields they increase resource efficiency by reducing the amount of raw materials used and the wastes or emissions produced. In addition their ability to produce the exact amount of material required allows reduction in stock and logistics costs which further increase resource efficiency. An example is the use of continuous flow reactors referred to earlier.



▲ **Figure 4. Using technologies such as injection moulding reduces the number of machining steps (© Robyn Mackenzie).**



▲ **Figure 5. Corning Advanced Flow Reactor™: an example of the new generation of resource-efficient reactors. (Source: CPI).**

These strategies are becoming more evident as they make good economic as well as environmental sense. There are large opportunities, if we can change behaviour.

STRATEGIES FOR BEHAVIOUR CHANGE

An interesting method under development is the use of dynamic-systems-based computer models of the flows of resources through time, which show where the largest gains in resource efficiency can be found. These models are crafted to represent a suitable level of detail of the manufacturing process, but are not so complex that the main drivers of a system's performance become unclear. The models also include feedback loops that represent reuse, remanufacturing and recycling options, which represent possible routes for materials at the traditional end-of-life points for products.

These software models are being developed by the Centre for REMS, which is applying its systems understanding and tools to individual businesses, such as those involved with polymer processing for the automotive industry. A dynamic systems model can be built to map the resource use by the whole supply chain. This mainly focuses on the flows of resources with time, but also incorporates costs or value where appropriate. The model starts with the existing, present-day supply system of the business to provide a baseline scenario. The model is then altered to represent potential new scenarios, for example reuse or remanufacturing, allowing a comparison of the existing and new systems. The benefit for the business is that it reveals likely outcomes of a particular strategy for resource efficiency, and where the biggest gains in efficiencies, cost reductions and sustainability can be made.

In conclusion, greater resource efficiency or closed loop manufacturing can be achieved by:

- Designing things that use little energy;
- Making or building them as efficiently as possible, preferably with reuse in mind;
- Thinking about resource flows before starting the design process;
- Thinking about resource flows through manufacturing systems;
- Thinking how wastes can be eliminated or used as fuels or feedstocks; and
- Driving collaborative interdisciplinary working.

More information about activities at CPI can be found at www.uk-cpi.com. ES

Professor Graham Hillier CEng, FRSA, trained as a metallurgist with Rolls-Royce. He also worked in manufacturing, business development and strategy for ICI, British Steel and Corus before becoming Director of Strategy and Futures at CPI. CPI is one of the seven innovation centres that make up the High Value Manufacturing (HVM) Catapult set up by Innovate UK. The HVM Catapult employs over 1,300 people working closely with academia, private industry and the public sector to convert the UK's leading science into products and services that can improve our everyday lives and add value to UK manufacturing. Graham is also Director of the Centre for Resource Efficient Manufacturing.

Dr Richard Court CEng is a Research Fellow in the Centre for Resource Efficient Manufacturing Systems (REMS). Richard has a diverse background spanning several industry sectors, with a variety of technical and project roles, a focus on performance of materials. Richard has previously worked on: renewable energy with Narec (National Renewable Energy Centre); materials joining research for TWI; military projects with the Defence Evaluation & Research Agency and UK Ministry of Defence; construction projects (Maunsell); offshore oil and gas (Wimpey Offshore); boat manufacture (CDRS); and semiconductors (Canon).

Julie Hill is Chair of the Waste and Resources Action Programme (WRAP), an Associate of Green Alliance, and an independent Board Member for the Consumer Council for Water. She is also the author of *The Secret Life of Stuff: A Manual for a New Material World* published by Vintage Books in 2011.

Professor Carolyn Roberts FRGS FIEnvSc FCIWEM CEnv C.WEM CSci is a 'Specialist' in the KTN, Innovate UK's knowledge transfer network. She is a Vice-President of the IES, the first Professor of Environment at Gresham College in London, and a past Chair of Society for the Environment.

IES: new members and re-grades

Members	Occupation
Rouba Abou-Atieh	Chemical Technician
Michael Brown	Senior Consultant
Simon Bunting	Assistant Air Quality Consultant
Eleanor Burke	Senior Energy Consultant
Adam Cheers	Environmental Consultant
James Clayton	Environmental Geophysist
Hannah Davies	Assistant Consultant
Eric Dede	Pollution Officer
Matthew Ellis	Environmental Scientist
Peter Gabriel	Air Quality Consultant
Rami Ghannam	Environmental Engineer
Natasha Glynn	Senior Engineer
Ian Halliday	Process Scientist
Lisa Hawtin	Principal Environmental Consultant
Glyn Hodgkiss	Senior Geo-environmental Specialist
Mark Holland	Environmental Protection Officer - Air Quality
Alan Humphries	Attorney
Mathew Jackson	Senior Geo-environmental Consultant
Lesley Jamieson	Senior Hydrologsit
Pauline Jezequel	Senior Environmental Consultant
Ann Keane	City Data Project Officer
Cheuk Yin Jason Lau	Air Quality Officer
Wing Yan Lee	Research Officer (Technical)
Ciara Longman	Senior Environmental Consultant
Andrew Lowe	Environmental Consultant
James Moss	Air Quality Officer
Kasturi Munasinghe	Assistant Consultant
Hugh Murphy	Senior Wayleave Officer
Diego Ortuzar Tellaeche	PhD Researcher
Victor Pallares	Environmental Planner
Laura Pennington	Environmental Consultant
Mimi Pierson	Associate
Sisira Ranatunga	Consultant Civil/Environmental Engineer
Christopher Rush	Founder & CEO
Louise Stock	Director
Nicholas Tymko	Director
Fiona Wark	Graduate

Associates	Occupation
Ali Baraka	Fundraising Assistant
Celine Bouvet	Environmental Scientist
Tomas Cawley	Environmental Scientist
Stephen Clare	Graduate
Leanne Crowe	Graduate
Craig Gothard	Graduate
Lauren Haynes	Assistant Air Quality Consultant
Rachel Hicks	Air Quality Officer
Prapamart Jackson	Graduate
Henri Macnish	Medical Record Administrator
Thomas McClure	Geo-Environmental Engineer
Christopher Moorin	Graduate Air Quality Scientist
Alastair Ross	Graduate
Stefan Whtie	Environmental Officer

Fellow	Occupation
James McNally	Technical Director and Head of Environmental, Social and Sustainability Management

Fellow is for esteemed individuals in environmental science and sustainability who are held in high regard by their peers

Member is for those individuals who have substantial academic and work experience within environmental science.

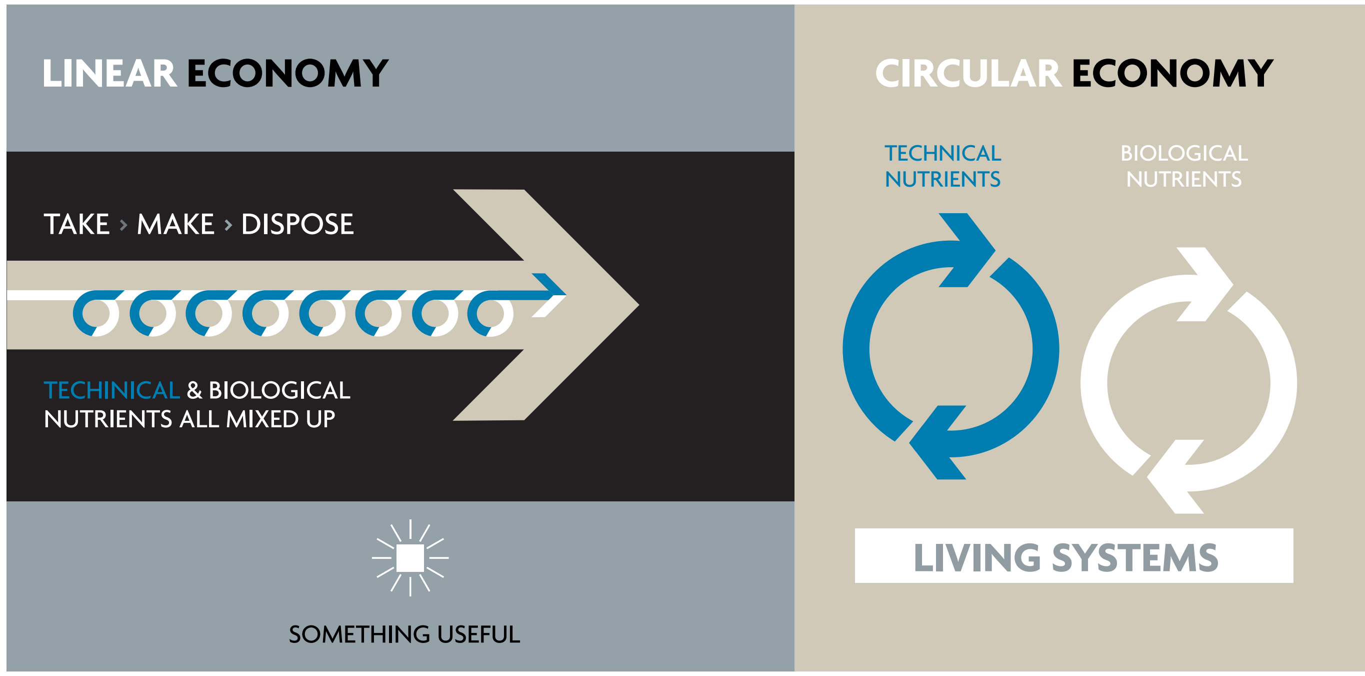
Associate is for individuals beginning their environmental career or those working on the periphery of environmental science.

Affiliate is for individuals with an interest in environmental issues but don't work in the field, or for students on non-accredited programs.

Joining the IES helps your professional development. Whatever stage you are at, the IES has membership services that will help you gain recognition and progress to the next level. Members come from all areas of the environment sector, wherever jobs are underpinned by sound science.

What makes material recovery from high-value products viable?

Roger Morton analyses the factors that increase diversion of materials from landfill in high-value products such as cars.



▲ **Figure 1. To develop sustainable and efficient industrial systems the challenge is to shift from a linear to circular model of production and consumption. Original source: © Graham Pritchard / Ellen MacArthur Foundation (after W McDonough and M Braungart).**

Most materials can be recycled and recovered with enough time and energy. However, only some materials are economic for industry to recycle at any given time. This paper will explore what those boundary conditions are, noting that some of them relate to the chain of businesses that supply manufacturers with raw materials, not just to the materials themselves. This will help to establish what the circular prospects for novel materials might be in future.

The challenge is to move from a linear to a circular model (**Figure 1**).

THE CIRCULAR ECONOMY FOR CARS

The blue boxes in **Figure 2** show the traditional linear production model, from component manufacture to car assembly to distribution and sale. Then a typical car in the UK will have three or four owners over about 10 years before it reaches the end of its useful life.

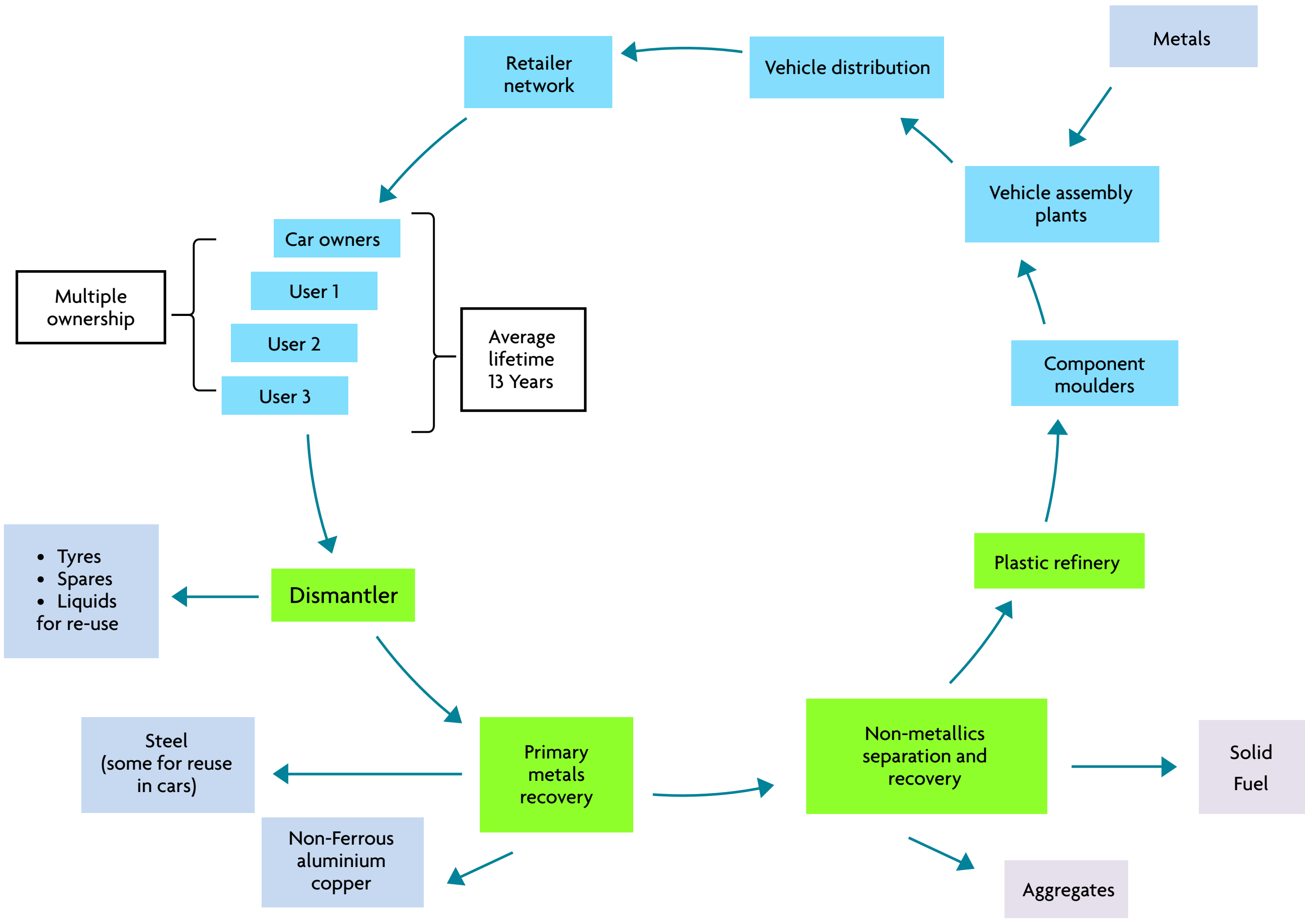
The green boxes show the new circular supply chain that is developing in the UK and the rest of Europe. A collection company takes the car from the last owner to a dismantler (officially called an authorised treatment facility). The dismantler removes all components deemed by law to be polluting (such as tyres and fluids), along with air bags and other components with high value (such as batteries, emission catalyst, certain spares, alloy wheels and sometimes the whole engine), for separate recycling or reuse. The depolluted shell is then crushed and shredded, and steel and non-ferrous metals (copper, brass and aluminium) are automatically separated (see **Figure 3**). The recovered scrap metals are sent to steel makers and non-ferrous smelters to make high specification metal materials which will be made into new products, including cars.

However, an increasing percentage of vehicle shells, currently about 30 per cent by weight, are made up of novel materials, a fraction that is growing as plastics, textiles and composites are increasingly used to reduce weight and energy use while the car is being driven. Companies are now introducing large-scale and innovative processes to recover these high-grade plastics and other non-metallic materials so that they can be used in new cars, completing the circular economy for vehicles. The stages of the end-of-life vehicle circular supply chain in practice are represented in **Figure 3.**

A CIRCULAR ECONOMY FOR HIGH-VALUE PRODUCTS

High-value products tend to be highly priced because they are complex and because they incorporate significant design value and intellectual property. This makes them expensive compared to the base value of the materials that they contain. For example the Colorado-based tear-down company IHS reports that the cost of the components in an iPhone 6 Plus is around US$200, compared to a retail price of US$749[1]. The difference reflects the cost of assembly (small) and the less tangible value of Apple's brand and its knowhow (huge).

The low relative price of the raw materials may cause policy-makers, manufacturers and consumers to



▲ **Figure 2. The automotive circular supply chain (Original source: Keith Freegard, Axion Recycling).**

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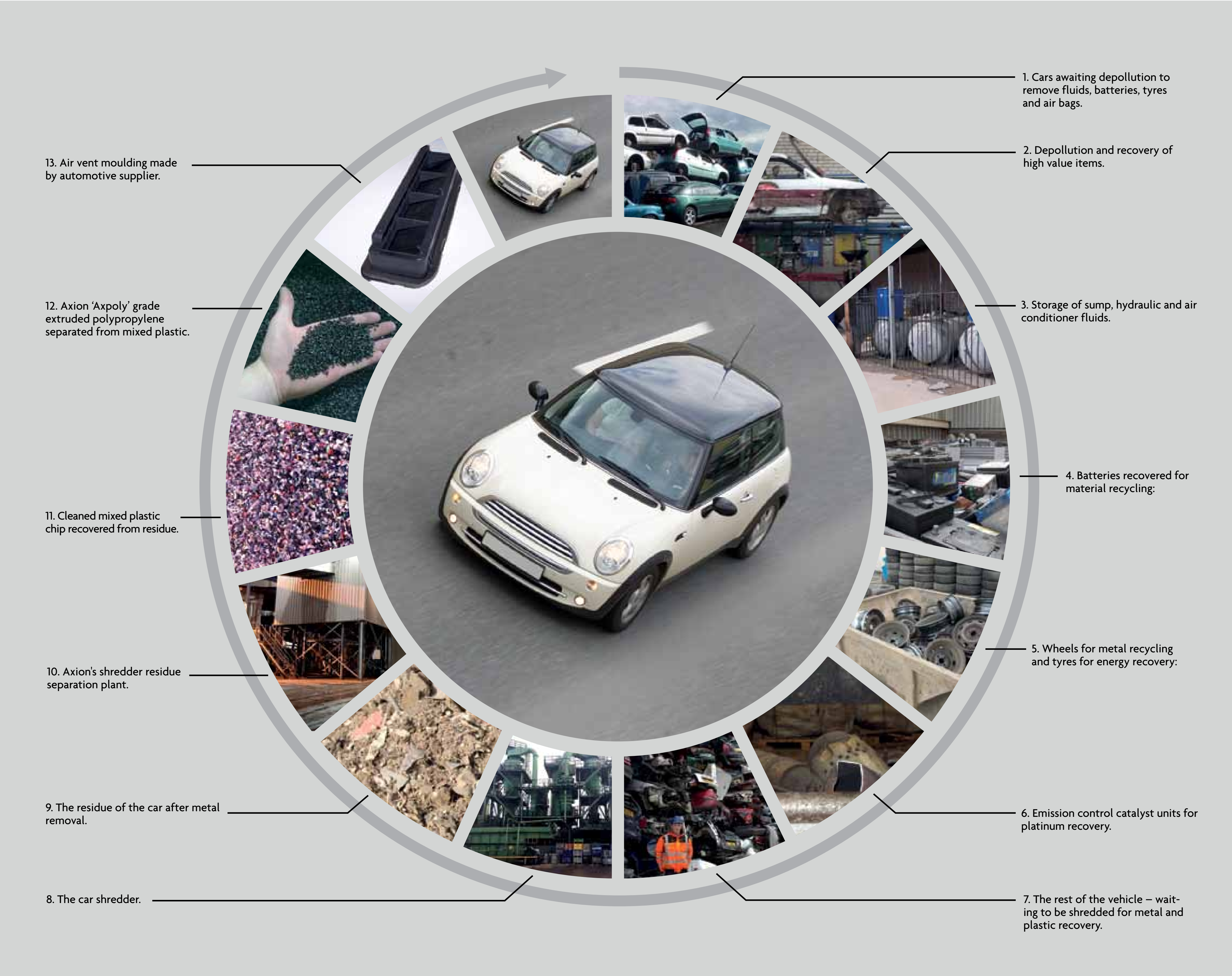

▲ **Figure 3. The automotive circular economy in practice: end-of-life cars are broken down so that the different elements can be fed into the manufacture of new cars. (Mini cooper image © alma_sacra. All other images courtesy of S Norton & Co. Ltd.)**

discount the importance of building circularity into their supply chains, but these materials are often undervalued by today's commodity trading markets. Material prices today reflect only the current and historic supply–demand balance. They do not realistically reflect the likely future shortages of base raw materials, particularly hydrocarbons and metals.

"To eliminate the concept of waste means to design things – products, packaging, and systems – from the very beginning on the understanding that waste does not exist...."

In addition to the risk of material scarcity resulting from growing global demand and decreasing natural resources, there are other reasons why designers of high-value items should look to build features into their products and their supply chains that make it easier to recover both individual components and base materials (what is beginning to be called 'circular thinking'). For cars, these include:

- **Meeting legislated targets**. For example, the EU End-of-Life Vehicle Directive now places an obligation on car makers to achieve 95 per cent recycling and recovery at the end of the car's useful life. This is when the last owner of the vehicle decides that it is no longer economic to repair the vehicle to keep it running.

- **Conserving the Earth's resources**. Experts in life-cycle analysis state that 80 per cent of a product's life-cycle impact is designed in[2]. For most high-value items, including cars, there are three main elements to the life-cycle impact of the product:

  1. Impacts associated with extraction of the base materials (such as oil, metals, minerals) and with manufacturing (machining, welding, moulding, assembly, transport);

  2. Impacts associated with car use (including energy consumption, emissions to air, land or water, and noise). By reducing weight, improving engine efficiency and improving aerodynamic performance, European car designers have made huge strides in this area over the past 20 years,

to the point where the impact of the primary materials and construction of the car is starting to become more significant. At a WRAP conference in May 2014, Jaguar Land Rover estimated that extraction and manufacture of the base materials for the new Range Rover will comprise 27 per cent of the whole life impact of the car. Assembly and transport of the vehicle will account for 2 per cent and the balance will relate to energy consumption in the use phase; and

3. Impacts associated with end-of-life disposal (such as emissions to air, land or water, persistent pollutants, and carbon from incineration). End-of-life impacts from cars today are very small compared to the other elements of the cycle, partly because all the metals and increasing amounts of the non-metals are recovered (with lower impacts from the recovery process than primary extraction). Beyond that, the components that are landfilled are largely mineral or plastic, which do not degrade and release carbon. The primary life-cycle benefit of end-of-life component and material recovery from cars is the substitution of primary raw materials with recycled product.

- **Customer expectations**. Production engineers for the BMW Mini were initially reluctant to accept components made from recovered plastic because of concerns that any change to the supply chain might cause disruption. However BMW's designers and marketing staff were very keen to respond to consumer expectations for increased recycled content.

CARS AND THE CRADLE-TO-CRADLE CONCEPT

McDonough and Braungart noted in *Cradle to Cradle*[3] that:

"To eliminate the concept of waste means to design things – products, packaging, and systems – from the very beginning on the understanding that waste does not exist…. Valuable nutrients contained in the materials shape and determine the design. Form follows evolution, not just function"[3]

BOX 1: ALUMINIUM STEEL AND COMPOSITES

Tata Steel have published a life-cycle impact study for carbon emissions that compares the construction and use phase impacts for the front end module of a typical European C-class car, when made from aluminium, steel and two different composites[4].

The steel front end module is heavier than the aluminium equivalent and therefore creates more impact during the use phase, but its embedded carbon impact from original manufacture is around one-third of the impact of the slightly lighter aluminium equivalent. One of the composite alternatives is similar in embedded carbon and use-phase impact to steel but the composite cannot be recycled with current technologies, while the steel is highly recyclable and can substitute virgin steel when recovered. Of course this study refers to the impact of only one vehicle component and ignores many of the other constraints that a designer has to consider, including the cost of manufacture, corrosion resistance and repairability.

(© Carloscatilla)

In other words, all designers should be designing products:

- With materials that have minimal environmental impact in their manufacture; and
- So that their materials can be captured, separated and recycled into equivalent value materials at end of life.

Designers put huge efforts into reducing energy consumption during the use phase of their products. For cars, this has led to increased use of aluminium and plastic in order to reduce weight, substituting steel and wood. The carbon impacts of making aluminium and plastic are substantially higher (see **Box 1**).

However, at the design stage there is often little regard for end-of-life material recovery. At a recent conference of over 100 Midlands car designers, a show of hands suggested that only one participant was aware that, since 2005, car makers have been responsible for ensuring that a specified percentage of their product is recycled at the end of its life; circular thinking has not yet permeated through to designers of high-value items. This is disappointing because designers, through their choices, can have a huge impact on the recoverability of the materials in their products.

Consider the two car bumpers shown in T**able 1**. A circular thinker might call the current Porsche bumper a monstrous hybrid! The complex structure and multilayer composite material with thermoset binder is almost impossible to recover as a useful material. Energy recovery (through incineration) or landfill are really the only commercially viable options, despite their negative environmental impacts. Conversely, the older Golf bumper design is heavier and less aerodynamic, and therefore uses more energy over the life of the car, but it is readily removable for reuse and its unpainted monomaterial structure means that it is attractive to recyclers.

The experience of car recyclers is that designers can be incredibly creative and, once given a new challenge and a new set of constraints, they respond quickly with innovative solutions. There are many ways in which the positive features of the modern Porsche bumper could be retained while adding 'circular' attributes. For example, the shape and the fixings could be adapted to make it easier to remove for reuse or repair, and the material could either be self-coloured or the coatings could be made compatible with the bulk material of the bumper when recycled. The composite structure of long glass or carbon fibres with a thermoset binder could be replaced

▼ **Table 1. Comparing the attributes of two car bumpers (VW Golf image: Tony Harrison (www.flickr.com/photos tonysphotos /2706674841) used under Creative Commons; Porsche image © Zygotehasnobrain)**

1980s VW Golf	2010s Porsche
Heavy components	Aerodynamic – low drag
Simple design	Complex structure
Monomaterial – thermoplastic	Composite material with thermoset binder
Unpainted finish	Coated finish
Releasable fixings	Complex fixings

FEATURE

by an alternative composite with a thermoplastic or solvent-soluble binder, where both the fibres and the binder can be recovered for reuse in new products.

New processes would have to be developed by recyclers to separate and recover these materials, but these types of process have been tested in other applications and there is no shortage of innovation or appetite for investment in the recycling sector if value recovery can be demonstrated. The way to achieve the best outcome is for manufacturers and recyclers to work together at the design stage in order to understand and address each others' constraints (**see Box 2**).

BOX 2: DESIGN CRITERIA THAT AID RECYCLABILITY

From the point of view of a recycler, the following design criteria could usefully be added to the many constraints that a designer of high-value products has to consider:

- Use simple, monomaterial components;
- Minimise the number of polymer types used in a product. For example, some car designers have introduced guidelines encouraging designers to use only certain families of polymer grades, which they know are easier for recyclers to identify and capture;
- Use thermoplastics – not thermosets or rubber which cannot be remelted;
- Design components with fixing arrangements that are 'releasable' in the bulk shredding processes used by recyclers, so that they can be sorted by hand or machine; and
- Avoid:
  - composites
  - fillers and fibres
  - metal inserts, clips, threads
  - paint, coatings, fabrics

OTHER FACTORS FOR SUCCESS

A circular business model requires everyone involved in the product supply chain to become involved practically in 'stewarding' the materials used in the product, from 'cradle to cradle'. Specifically, the stakeholders need to:

Communicate the composition of products along the supply chain. Recyclers spend a lot of their time trying to work out what materials are contained within the products that they are trying to recover.

As an example, Axion recently needed to invest time and deploy sophisticated analysis to quantify the material composition of three designs of utility meter, to support a client who intended to recycle several million units over the next few years. Recycling would have been faster and easier if the original meter designers had provided very detailed data on the grades and quantities of material in their products. The technical and commercial risk would have been reduced, and the client may have been able to recover the materials to higher-value outlets. From the designers' point of view, they would have needed to provide the information in a way that did not compromise their confidential knowhow.

Segregate end-of-life materials from general waste. Once a high-value complex product such as a laptop or a medical electronic device enters the general mixed waste stream, it is very difficult to recover much of its intrinsic material value. It is much easier if complex products are kept separate and treated together in categories, ideally down to the individual model. There are many low-cost ways of achieving this, and some even add value for suppliers of new products by building customer loyalty. For example, retailers of new products can offer takeback services so that when a customer buys a new product they can drop off their old one, either free of charge or in return for a credit on the new product. The retailer can use back-load haulage to send the old products back to the distribution hub for collection by a recycler. Alternatively, products can be marked with a web link that connects the last owner of the product to a drop-off point or a freepost return service to a central collection hub. Mobile phones and toner cartridges are already collected in this way and a profitable and very environmentally beneficial remanufacturing industry has developed as a consequence.

> **"there is no shortage of innovation or appetite for investment in the recycling sector if value recovery can be demonstrated"**

Develop new product-specific remanufacture and recycling technologies. As collection routes develop for segregated streams of high-value products, it becomes economically viable to develop specialist remanufacture and recycling techniques. The market has typically responded quickly to these new opportunities. As an example, this has already happened in the UK for computer hard drives, where end-of-life drives are removed, wiped and tested, then packaged for export using the same equipment that is used for new drives, and to the same performance standards[5]. As another example, Caterpillar has put remanufacturing at the core of its business strategy. Its equipment is designed from the start with remanufacturing in mind and its recovered parts are sold with a full Caterpillar warranty[6].

BENEFITS OF THE CIRCULAR ECONOMY

The benefits of a move to circular economy supply chains have been well documented. They include:

- **Lower carbon impact**. Axion has quantified the life cycle of its high-grade polymers recovered from end-of-life cars and can demonstrate a 60 per cent carbon impact compared to the equivalent virgin polymer. The principal life-cycle benefits derive from the fact that the polymers that enter the recycling process are already available above ground and are already complex, long-chain polymers. They only have to be separated by polymer type, cleaned up and remelted, which are all relatively low-energy processes. Virgin polymers are derived from oil, which has to be extracted from the ground, converted to monomer and then polymerised, with significant energy costs and yield losses at each stage. The principal disadvantage of current recycling plastic processes is that they are much newer technologies and therefore operate at a much smaller scale than the polymer recycling processes that have developed over the past 70 years. Bulk polymer manufacture demonstrates big economies of scale.
- **Stable material costs**. The costs of the circular supply chain are decoupled from widely fluctuating commodity prices. Plastic recyclers in the UK are increasingly agreeing deals with manufacturers that are linked only to retail price inflation or even fixed for the life of a specific moulded product. This reduces risk for the makers of complex high-value products, because virgin polymer suppliers necessarily have to link their prices directly or indirectly to the oil price.
- **Closer and more trusting commercial relationships between partners** in the supply chain as a consequence of the collaborative work that is inevitably required to make circular supply chains work.
- **Employment generated**. The recycling and remanufacturing industry is growing fast in the UK. By the nature of the complex separation operations that are required it tends to require a significant labour input, both low skilled for sorting and high skilled for development and operation of the new processes that are required.
- **Happy customers!**

THREE PRINCIPLES

All parties gain from change to a circular economy: manufacturers, consumers and the environment. Axion's experience of how to achieve this suggests three simple principles:

- Broaden the design brief for new products to include circularity, so that everyone thinks about end-of-life recovery at the design stage;
- Be challenging in material choice – and keep it simple, even if novel; and
- Improve information flow along the supply chain. **ES**

Roger Morton is a chemical engineer and trained with Unilever. He holds a PhD in integrated chemical process design from Manchester University.He founded Axion Consulting and its production division Axion Polymers with fellow director Keith Freegard in 2001. Over the 20 years prior to forming Axion he held general management positions with both start-up and established companies in chemicals, textiles and building materials.

Axion Recycling is a leader in the UK resource recovery sector, and has designed, built and now operates two large facilities. The first, in Trafford Park, processes end-of-life vehicle shredder residue to recover valuable materials such as minerals, high-value metals and solid recovered fuel. The second, in Salford, makes high-grade 100 per cent recycled polymers from a mixed-plastic concentrate that is generated at the Trafford Park site. The overall objectives of the combined operation are value recovery and landfill diversion, in compliance with the EU End-of-Life Vehicle Directive. The operation achieved over 95 per cent material recycling and recovery in 2014.

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Reaching around the circle from design to resource recovery

Julie Hill talks to **Steve Lee** and **Sophie Thomas**, who work in different parts of the supply chain but share a common goal: better product design for better recovery.

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Steve Lee is CEO of the Chartered Institution of Waste Management (CIWM) and of Resources and Waste UK, the latter a result of the recent partnership between CIWM and the Environmental Services Association (ESA). He has 35 years' experience of what he calls the one-way economy – waste management and a lot of landfill – but has a mission to put resources back to work.

Sophie Thomas is Director of Design at the Royal Society for the Encouragement of Arts, Manufactures and Commerce (RSA) and creator of The Great Recovery project, which aims to understand and boost the role of design in delivering a circular economy. She is a designer by trade, interested in sustainability, behaviour change and communications. She is fascinated by how we think about 'waste' and its impacts.

You are both leading professionals from different ends of the resources chain. I'm interested in your experiences, visions and dreams. But to start at the beginning: in your experience, how far do you think the term 'circular economy' is understood by the organisations and individuals you work with?

Sophie I was recently with 40 people from many disciplines in one of our workshops, looking at the design shift from product to services, and most had heard of the circular economy but this is not the norm. The big businesses that are making efforts to understand their supply chain have heard of it and those businesses that are 'future proofing' their resource inputs understand the pressure points, but most of the general public have not come across it.

Steve CIWM did a survey among its members asking that question, and those responding did understand it. But people want to know what their role is – what the future of their business is and what is needed of them. Some businesses are taking it very seriously and are very excited, whilst some are paying lip service.

If the circular economy is not well understood, what do you find the most successful way of explaining it?

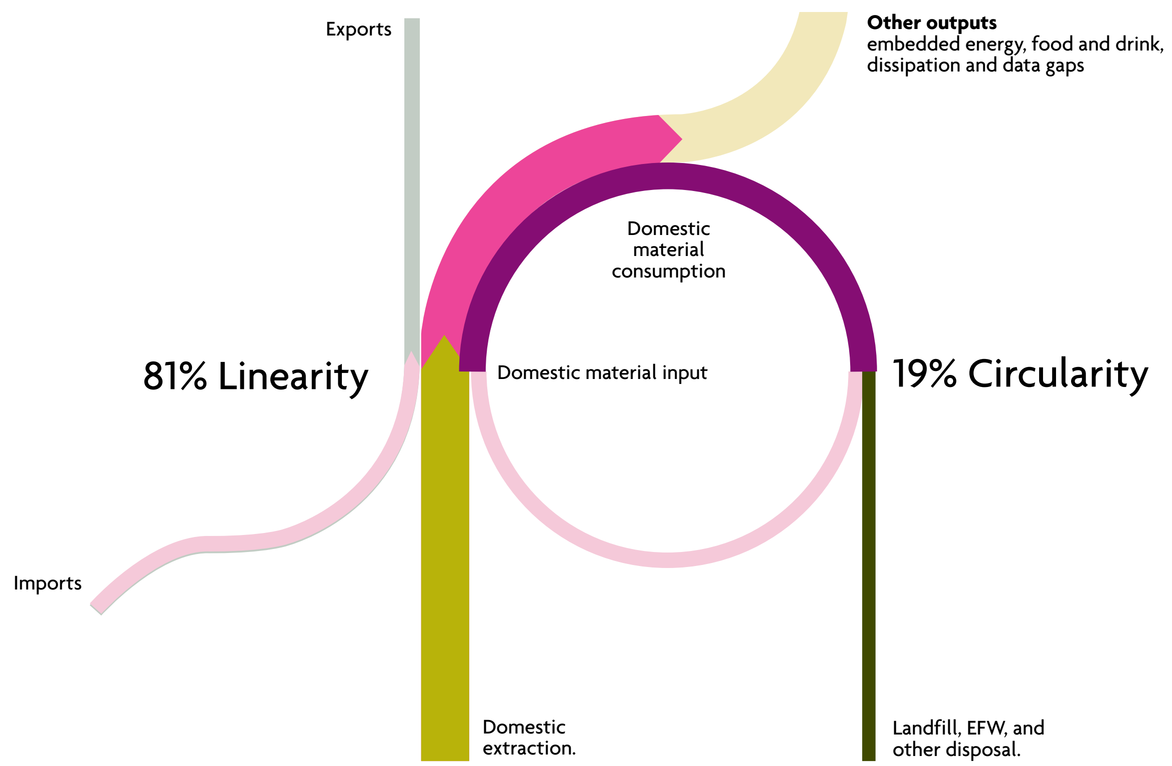
Sophie Being a designer, I start with pictures that tell stories. We use the Green Alliance's '19 per cent circular' image, which itself was drawn from the government's Waste and Resources Action Programme (WRAP) data (see **Figure 1**). We talk to people about their own experience, how things fall out of the circle and travel a linear journey straight to landfill, and about the potential of recapturing the value. We also show them the physical challenges of recovery, often because of a product's current design. In our 'tear down' workshops, participants are invited to try to dismantle their stuff and the reality is that it can be extremely difficult! It's not just about components that make up our products, we tear down to the materials themselves, and add in the system's complexities like volume targets or collection contracts. We are not collecting materials from households in the most helpful way from a circular system point of view. All this gives a bigger picture.

Steve Everyone should visit a landfill, just to understand the scale of what we throw away. I call it 'the fear, the farce and the challenge'. Fear comes from seeing the landfill. The farce is the environmental 'rucksack', the enormous quantities of waste materials, energy and water that lie behind every product – the rock removed in mining, or the offcuts from the manufacturing process, or the packaging used to bring it to us. The challenge is how to change this through design. That is why Sophie's work is so important: it brings together designers with people who understand the other end (the resource managers) and those who understand people's relationships with their stuff and why they behave as they do.

If circular economy approaches are being taken up, what do you think the reasons for that are? Cost saving? Reducing environmental impact? Fashion? Reputation?

Sophie The narratives we hear are not specifically about price (though it can be a big barrier), or 'peak stuff'. They are about price volatility, a need for certainty to predict business futures and a desire to do more manufacturing in the UK. I also think that social responsibility is becoming a bigger driver – the feeling that this is the right thing to do.

Steve Scarcity is an issue for some resources – take indium for example: a relatively rare metal that is the



▲ **Figure 1 . Diagram illustrating the current circularity of the UK economy (Courtesy of Green Alliance and WRAP).**

secret behind touch-screen technology. The truth is that there's only so much of it on the planet. We have to use it wisely. Resource security in a more political sense is a driver for others (e.g. coltan, the ore for niobium and tantalum). But I agree, it's volatility that scares people. Rolls Royce are asking where the yttrium they need for turbine blades will come from in 50 years' time. There is a growing perception of commercial advantage from recovering resources. At the same time, the market does odd things – the price of recovered plastic from white goods has recently halved because virgin plastic prices have fallen with the oil price. This has undermined the economics of the whole process and could lead to widespread renegotiation of contracts in this sector.

"Everyone should visit a landfill, just to understand the scale of what we throw away."

Sophie There is also a driver that is about research and development. Talk of the circular economy has given companies a reason to test some innovation around different business models that do not rely on unit profit, and this is now being supported by funding bodies such as Innovate UK.

What do you yourselves think are the key benefits?

Steve In the longer term, the benefit is being able to live within our environmental means. In the short to medium term, the benefits are jobs, growth and export opportunities. We can export the knowhow about the circular economy as well as the products and materials themselves.

Sophie I agree – the circular economy could be the route to reskilling the country. We know we are in danger of losing skills in industries such as textiles and ceramics over the next decade, so we need to be reinventing manufacturing to keep and evolve these skills. We should be considering bringing these industries back to the UK, which would also help to reduce environmental impact. It is a big challenge – but then design is good at big challenges and this one is about opportunity, and disruption of existing models.

If you could wave a magic wand and reduce one big area of environmental impact, what would it be?

Steve Food waste – because of the land, fertiliser, carbon and methane that is involved in producing it.

Sophie If we agree that 80 per cent of the environmental impact of the product is predetermined at the design stage, then we should be using this fact and putting pressure on those who write the design briefs to consider the second and third life of our products. We are very good at developing and designing complex things but not so good at understanding how to disassemble them. The problem is that so many products combine so many materials: 18 different materials in a mattress, for example. And without a 'bill of materials' on all our products, reprocessors don't know what's in our things, why it was thrown away, and therefore what the material reuse value could be.

When you think about 'novel materials', what comes to mind?

Steve Graphene – graphene could replace indium in touch screens. It might be the answer to all sorts of questions. It's simple to manufacture and readily available – it's a miracle material at the moment but could be really common, with all sorts of applications in the future. Also carbon fibre – it will shortly explode into the market in a variety of products. At the moment,

▲ **Figure 2. A 'tear down' workshop taking place as part of the RSA's Great Recovery project. (© The RSA Great Recovery)**

the waste industry can't do anything with it, so we need research and development for the processing technology to recover it. High-performance ceramics in car engines and brakes are also difficult to recover. And we shouldn't forget about laminates (layering of different materials), which always pose recovery challenges, but their increasing use is likely to push development towards more recoverable forms. And for some materials it might be a case of reuse rather than recovery – we can't get the neodymium out of supermagnets, so we need to keep the magnets themselves in use.

Sophie We have been looking at building and construction, where novel materials are radically changing the way our buildings perform. For example there are different coatings for glass, which can self clean or are water repellent but that burn up when the glass is remelted, so can't be recovered. As a general rule we only have crude means of separating materials that sit within our products – for instance, the metals in phones that are shredded and melted in a smelter. Only 17 out of 40 elements can be recovered and some that have high demand, like neodymium, are not yet retrievable. At the moment, products are mainly designed for ease of manufacturing. When we look at computer hard drives, they are all different – different shapes, designs and weights even when they are fitted inside computers from the same company – because they are effectively a group of components that are brought together in a factory and mass assembled. This would be a perfect opportunity for modularity and, as Steve says, that's the way to go for maximizing value in reuse and recovery. Taking the magnets off a hard drive before shredding (which would otherwise render them worthless) keeps the value. LEDs are another example of a groundbreaking but complex product with a future wastestream issue as there is presently no route for recovery. The solution is to design a business model around leasing the service (the light) not selling the product (the lightbulb). That way the company designs for long life and has the opportunity to get the value of the materials back.

Are you experiencing any novel materials in your work to date?

Sophie We experience more than we realise. Laminates, composites, textiles with Teflon. Many are used because they are lighter than materials they replace – for example materials used for more efficient insulation. We are not against technical innovation but some issues are just not in the minds of those who create the materials, and often the 'end of life' is never even considered, such as the plastics that end up in the ocean. Will novel materials pose that kind of problem? I start to feel like a bit of a party pooper asking all these questions, but they are actually very significant design challenges.

Steve We've always had novel materials – it just takes a while for us to get used to them and to learn how to manage them. A current 'bug-bear' novel material that worries us is the various forms of plastic film. There are competing technologies of even the standard polymers, and now there are biodegradable polymers and others, and it doesn't work to mix them in the recycling streams. My concern is that novel materials could be either invisible or indistinguishable from conventional materials, giving consumers dilemmas about which bins to put them in, and potential contamination problems in the collected materials.

What do you think are the main challenges posed by novel materials for moving towards a more circular economy?

Sophie I agree with Steve – it's back to bins – if people don't know what to do with products, they hide them in the 'everything else' residual waste bin.

Steve The challenge is making decisions as to whether a material is justified in the product if we take a lifetime view. In the future, we will have dependable life cycle assessment to help us. If the whole-life cost of a product or service is drastically reduced by using a novel material it's hard to justify not using it because it's hard to recycle. Professor Walter Stahel, often cited as the father of the circular economy, holds that no one has the right to unleash a new material until we have the answers, but I don't think that's realistic. We have to have new materials, and we need to learn how to keep them working or how we put them back to work!

Sophie I'm with Walter – the design process has to take into account recoverability. If we aim to embed the reprocessing with the manufacturing, we can have a win–win.

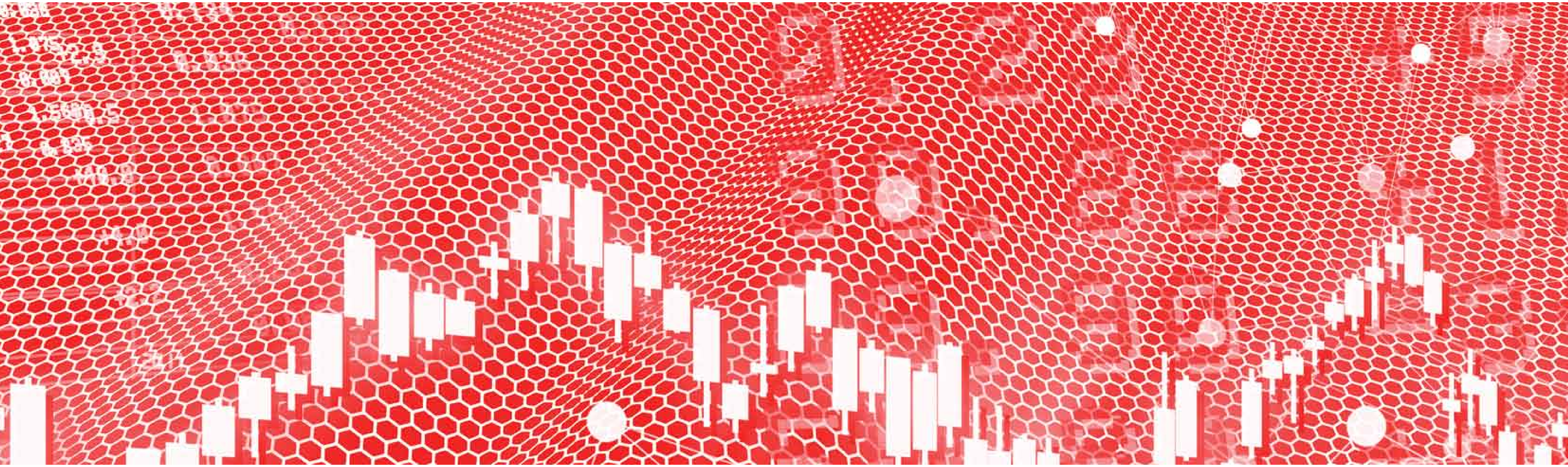
How do you think we could make resource recovery more mainstream?

Steve A much bigger range of university disciplines should cover resource efficiency, and we need more interdisciplinary working.

Sophie Yes, and the problem we have is that design as a discipline has no continuing professional development process, so it's hard to get designers out of the studios to get fresh perspectives, and to learn about the whole life of their designs – hence The Great Recovery project. And we need much more teaching on system design – how to design infrastructure and supply chains that take account of the need for recovery. Being a Chartered Waste Manager I can lean across to the other end of the life chain (the other side of the circle) and understand how the picture looks from that end. That is essential knowledge, and all designers should do it. ES

Julie Hill is Chair of the Waste and Resources Action Programme (WRAP), an Associate of Green Alliance, and an independent Board Member for the Consumer Council for Water. She is also the author of '*The Secret Life of Stuff: A Manual for a New Material World* published by Vintage Books in 2011.

CASE STUDY



Advanced materials and sustainability: the role of the Engineering and Physical Sciences Research Council

Lucy Martin and **Anna Angus-Smyth** describe how EPSRC encourage collaboration and provide funding in order to promote the development of sustainable advanced materials.

The field of Advanced Materials encompasses a huge breadth of materials research, including biomaterials for tissue engineering, materials for renewable and nuclear energy, high-performance metals, plastic electronics, composites, and meta-materials, which are designed from the atom level to have properties not found in nature. Each of these areas draws on UK research excellence in materials science, maths, physics, chemistry and engineering to tackle real-world materials applications.

One clear application of Advanced Materials research is in the evolution and strengthening of UK manufacturing, with obvious benefits to the economy. Currently, advanced materials are worth £197 billion a year to the UK market[1], which represents 15 per cent of GDP[2]. There are predictions that the global market for value-added materials (currently £80 billion a year) could rise to £250 billion by 2030[3]. Advanced materials have been identified by the UK government as one of the great technologies that will propel the UK to future growth[4]. They are part of the UK's high-tech industrial strategy[5].

As the UK's largest public sector investor in research and training in engineering and physical sciences, the Engineering and Physical Sciences Research Council (EPSRC) has invested over £430 million to secure the UK's position as a world leader in advanced materials research. This investment in fundamental materials research will underpin research and exploitation across sectors as diverse as electronics, medicine, energy, environmental science, and infrastructure. Current investment includes:

- £45 million of capital infrastructure, for equipment to support advanced materials research;
- EPSRC Centres for Innovative Manufacturing;
- The Graphene Global Research and Technology Hub; and
- 42 new centres for doctoral training (CDTs) to train the engineers and scientists of the future with skills and knowledge in materials-relevant research.

MATERIAL SUSTAINABILITY AND RESOURCE EFFICIENCY

Whilst research into new and novel materials is crucial to the UK, ensuring material sustainability and integrating resource efficiency into fundamental research must remain a key challenge. This strategic need was recently highlighted by *Materially Better Physical Sciences*[6] and *Reports from the Materials Research Exchange 2014*[7].

Sustainability and resource efficiency incorporates the full spectrum of the 'reduce, reuse and recycle' agenda, from the availability of raw materials through to the management of waste at the end of its useful life. The importance of sustainability is further supported by the European Commission's *Roadmap to a Resource Efficient Europe*[8] and the BIS/Defra *Resource Security Action Plan: Making the most of valuable materials*[9], which outline the need to promote and support research and innovation within this area.

Key future challenges will include aligning novel materials and processes with the circular economy and integrating sustainability into all areas of manufacturing, infrastructure and environment. There are also more specific challenges around biofuels, energy efficiency, and development of sustainable bioprocesses for chemical and material production.

INVESTMENT IN SUSTAINABLE ADVANCED MATERIALS

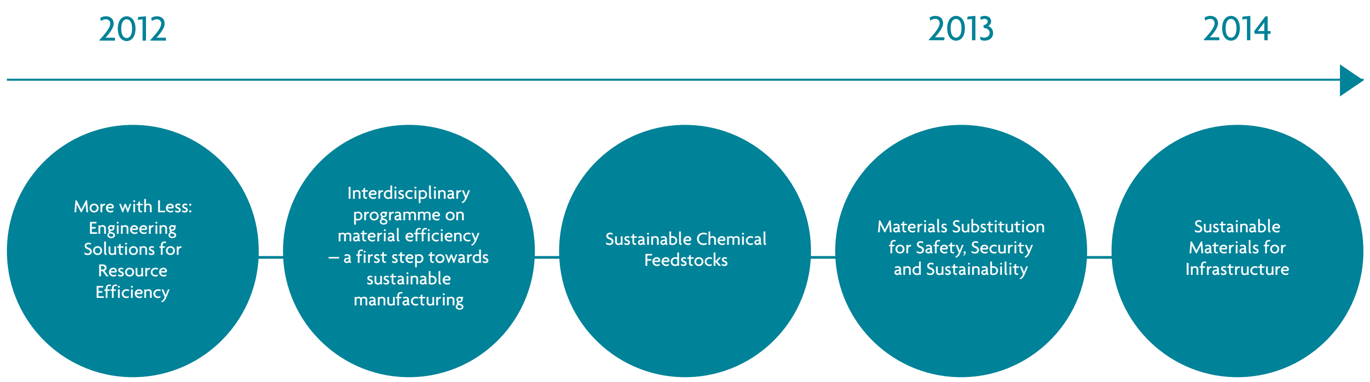
EPSRC has recognised the importance of research into advanced materials sustainability and has consequently invested over £60 million over the last three years in research relating to advanced materials sustainability. One of the most recent interventions was the EPSRC Materials Substitution for Safety, Security and Sustainability call. The uptake of alternatives to scarce and harmful materials is limited by our ability to process such materials. As such, this call aimed to increase UK research capacity in manufacturing substitutes for scarce and harmful materials by:

- Supporting research that addresses the manufacturing challenges of novel replacements for materials that are scarce, difficult to source, expensive or harmful to health and the environment;
- Accelerating the pathway from research on novel materials, through to their use in manufacturing products; and
- Promoting networking and collaboration across relevant disciplines and with industry.

The call funded 6 projects with a total value of £14.7 million, which spanned the advanced materials landscape and ranged from the sustainable manufacture of safe and sustainable volatile element functional materials, to the manufacture of cellulose fibres to replace glass and carbon fibres, to photovoltaic technology based on Earth-abundant materials. All of the funded projects involved extensive collaboration between industry and a range of sectors including chemical engineering, coatings, materials and ceramics.

EPSRC also recently led the sandpit called More with Less: Engineering Solutions for Resource Efficiency in response to the challenges raised by the research community in the Resource Efficiency Scoping workshop in 2012[10]. Sandpits are funding mechanisms used by ESPRC to generate new and innovative ideas by bringing together researchers from a very broad range of relevant disciplines.

The strategy behind this sandpit was informed by the European Commission's *Roadmap to a Resource Efficient Europe*[8] and the BIS/Defra *Resource Security Action Plan: Making the most of valuable materials*[9]. With the ever-growing concern of material and resource scarcity, EPSRC looked to the ingenuity of researchers to find long-term sustainable solutions around the three main challenges of dematerialisation, designing for resource sustainability and reusability at any scale. The sandpit funded 4 projects with a total value of £5.5 million.



▲ **Figure 1. EPSRC calls supporting resource efficiency and advanced materials research.**

BOX 1: THOUGHTS FROM NEIL ALFORD...

"Climate change is upon us, we are causing it and we need to sort it out. In October 2014 the European Council set very ambitious targets for greenhouse gas emissions, energy efficiency and on energy security. What does this mean for the UK? It means the gauntlet has been thrown down to find science and engineering solutions that are feasible, cost effective and above all sustainable. This is the challenge we in academia face and it is one we are perfectly capable of addressing.

In the area of materials science and engineering there is increased interest in sustainable solutions in the area of, for example, solid-state cooling with thermoelectrics or electrocalorics, with low-cost LED lighting and with polymer/organic light harvesting. Really important change is needed and it is up to scientists and engineers to deliver this change."

Professor Neil Alford is Head of the Department of Materials at Imperial College London and an EPSRC Physical Sciences Strategic Advisory Team Member.

The three funded research projects focus on extremely diverse aspects of resource efficiency.

- The first is looking at treatment of contaminated land in order to recover materials for future use and economic gain;
- The second is researching novel recycling and re-manufacturing processes, in order to stimulate a major change in composites' resource efficiency; and
- The third project considers how to create greater long-term emotional attachment to electronic products such as mobile phones, in order to limit electronic waste and improve recycling.

A key additional component of this sandpit was the funding of an engagement programme, CORE (Creative Outreach for Resource Efficiency), promoting creative public and user engagement around resource efficiency.

WORKING INTERNATIONALLY AND IN PARTNERSHIP

EPSRC has also been encouraging international collaboration within the area of materials efficiency. One such initiative was led through the G8 Research Councils Initiative on Multilateral Research Funding, which sponsored a suite of grants worth £2.1 million for international collaborations around materials efficiency for sustainable manufacturing. Canadian, French, German, Japanese, Russian, UK and US teams bring together different sets of knowledge, perspectives and experience in a concerted effort towards solving challenges related to topics such as remanufacturing, component reuse and recycling, new design methods, materials replacement, and extending the life of manufactured goods. UK researchers have been particularly successful, participating in six of the ten consortia and taking the international lead in three.

Another step towards incentivising international collaboration was through the EPSRC and National Natural Science Foundation of China call on Sustainable Materials for Infrastructure, which was designed to foster closer technological and engineering links between the UK and China in the area of multi-functional materials, energy-efficient buildings, novel concrete technologies and the materials 5Rs (reduce, recover, reuse, recycle and retain). The projects, which received £3 million in funding from EPSRC, range from how to develop intelligent coatings for windows to improve energy efficiency to the development of magnesia-based cements and concrete products for future energy infrastructure applications.

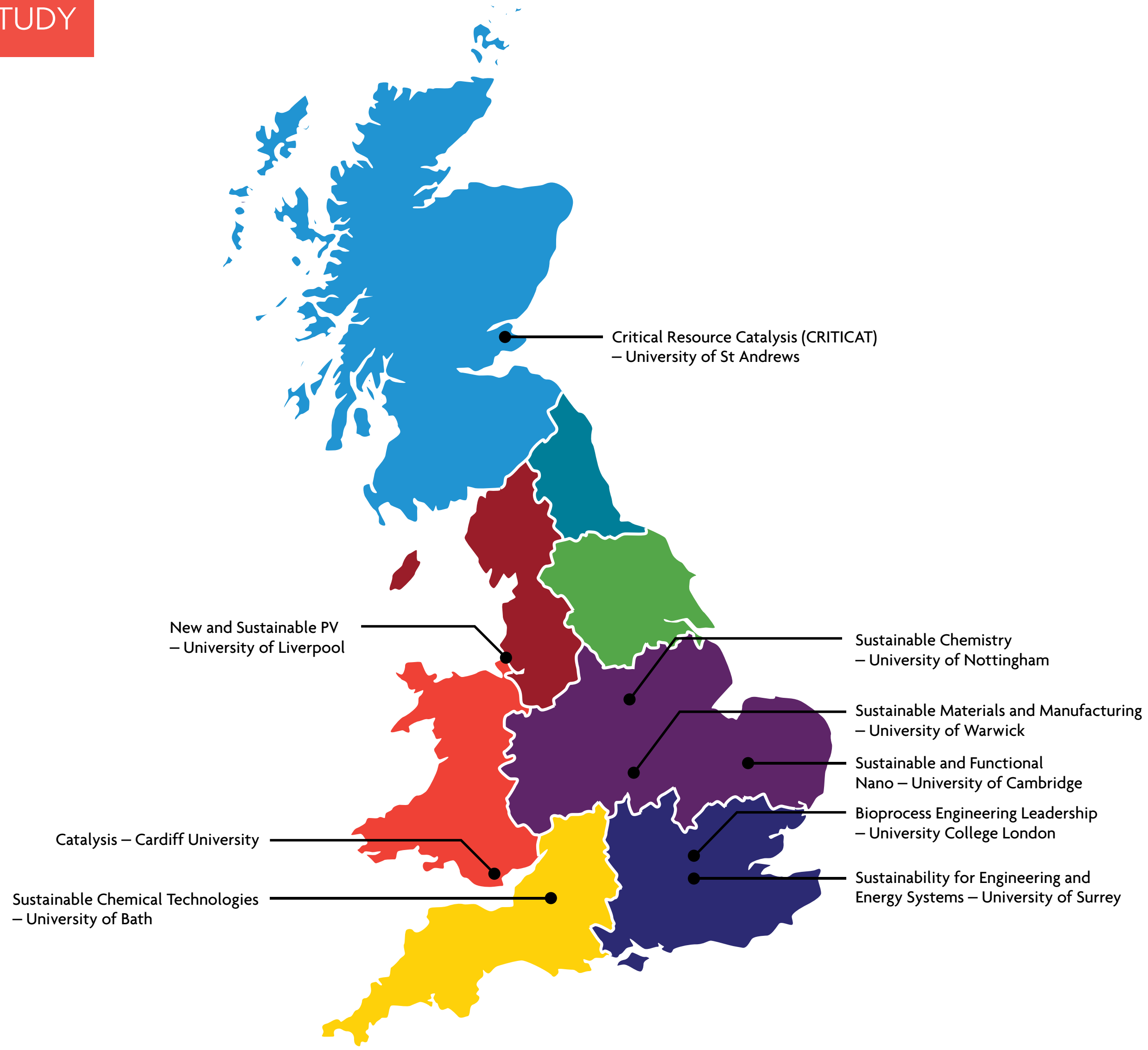
EPSRC has also been working in partnership with the Biotechnology and Biological Sciences Research Council (BBSRC) to focus research on the cost-effective production of chemicals and materials from sustainable and renewable feedstocks. Five multidisciplinary research projects that brought together diverse groups from across the engineering, physical sciences and biology communities projects were funded by EPSRC and BBSRC, at a total cost of £11.8 million. The projects adopted a systems approach and explicitly considered the pathway to manufacture, including issues of scale up, design, process engineering and product quality. Projects also involved extensive collaboration with industry, including manufacturing and industrial biotechnology companies.

BOX 2: THOUGHTS FROM JULIAN ALLWOOD...

"Around one sixth of the world's anthropogenic greenhouse gas emissions are caused by the production of steel and cement. We use these materials in vast quantities – 200 kg of new steel is made each year for every person on the planet – and we won't replace them, because we don't have anything else available in the same volume. They're also already made efficiently – one third of the cost of making steel is the cost of energy – so regardless of the environment, the industry has always been motivated to exploit every possible energy efficiency.

Therefore if we really want to reduce the environmental impact of material, we have to use much less of it, and this is technically relatively easy to achieve: materials are cheap but labour is expensive, so we have developed the habit of using excess material to save labour. The UK INDEMAND Centre exists to explore how we can bring about a transition to using materials more efficiently – through demonstrating technical possibilities, through exploring the preferences of owners and how this can be influenced by design, and through evaluating potential interventions in economics and policy."

Professor Julian Allwood is Professor of Engineering and the Environment at the University of Cambridge and Director of the UK INDEMAND Centre.



▲ **Figure 2. EPSRC-funded Centres for Doctoral Training relating to advanced materials and sustainability.**

OTHER EPSRC INVESTMENTS

Other significant investments that contribute to the UK research capability in advanced materials sustainability are:

- The EPSRC Centre for Innovative Manufacturing in Liquid Metal Engineering led by Brunel University, which is developing solidification processing technologies for metals such as aluminium, magnesium, titanium, nickel, steel and copper, and their alloys;
- The EPSRC programme grant on Light Alloys Towards Environmentally Sustainable Transport: 2nd Generation Solutions for Advanced Metallic Systems at The University of Manchester, which is developing high-performance light-alloy systems for automotive and aerospace applications;
- The EPSRC UK INDEMAND, a national research centre for reducing industrial energy and material use in supplying UK needs; and
- A research programme on Designing Alloys for Resource Efficiency – A Manufacturing Approach, led by the University of Sheffield, which is using basic science to understand the role of strategically important elements, to design new alloys with greater resource efficiency and to optimise the processing route for the new alloys to give supply chain compression.

PLANNING FOR THE FUTURE

EPSRC is committed to training the next generation of research leaders, and has invested £500 million in CDTs, which will train over 7,000 students. This investment includes nine funded centres related to material sustainability, designed to produce a new generation of engineers and scientists for industry and academia trained to think about sustainability in materials and processes (see **Figure 2**). EPSRC also sponsors students through the Doctoral Training Grant and Industrial Cooperative Awards in Science and Engineering.

EPSRC are currently in the process of developing the next delivery plan. It is working with the research community to scope future activities and strategies within Advanced Materials, as well as working closely with Innovate UK to maximise opportunities for the long-term benefit of the UK. Advanced Materials is a priority areas for EPSRC and integrating resource efficiency considerations into fundamental research to ensure that technologies are developed and implemented in a sustainable way across the whole innovation system is a key pillar of EPSRC's future Advanced Materials strategy.

EPSRC is the main UK government agency for funding high-quality basic, strategic and applied research and related postgraduate training in engineering and the physical sciences, to help the nation exploit the next generation of technological change. It invests more than £800 million a year in a broad range of subjects – from mathematics to materials science, and from information technology to structural engineering.

Further information on any of the points discussed in this article can be found at www.epsrc.ac.uk and gtr.rcuk.ac.uk. **ES**

Lucy Martin is an Engineering Manager at EPSRC and is responsible for the Materials Engineering portfolio, which involves working with the research community to achieve EPSRC's aim to put the UK at the forefront of international research. Lucy has a background in electrical engineering and prior to her current role Lucy was part of the project team for the Foresight Future of Manufacturing Project at the Government Office for Science. She has worked at the National Renewable Energy Centre on electric vehicle technologies.

Anna Angus-Smyth is Engineering Manager for Resource Efficiency at EPSRC. Anna has worked within the engineering theme at the EPSRC for the last two and a half years, previously looking after medical engineering, and currently responsible for the Resource Efficiency portfolio. Prior to working at EPSRC, Anna's background was in Physical Chemistry.

Remanufacturing transformers and switchgear

Rachel Waugh and **Clare Adams** describe the options for and advantages of making the manufacturing processes more circular.

© Jorg Hackemann

Remanufacturing is the process of disassembling, cleaning, repairing and inspecting an end-of-life product to return it to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product. Unlike material recycling, remanufacturing preserves many of the components in the original product for direct reuse, which results in savings in raw materials, energy, labour and money. There is normally a commensurate reduction in the environmental impact. A wide range of goods currently include remanufacturing: automotive components such as engines, consumer goods such as printer cartridges, and ICT equipment such as desktop computers.

Remanufacturing has been demonstrated to be commercially viable and technically feasible when three conditions are met:

1. **Value:** the product is valuable because of the materials it contains or because of the labour used to manufacture the original product;

2. **Evolution rate:** the product has a slow rate of technological change, is not subject to legislative restrictions, or can be upgraded to overcome these challenges; and

3. **Reconstructability:** both the product design and the existence of technical expertise allows the product to be disassembled, cleaned and repaired, reassembled and tested.

"Unlike material recycling, remanufacturing preserves many of the components in the original product for direct reuse, which results in savings in raw materials, energy, labour and money."

This case study explores how one UK company, Slaters Electricals, has developed a range of circular business models for power distribution equipment (such as transformers and switchgear) centred on their expertise in remanufacturing.

WHAT ARE TRANSFORMERS AND SWITCHGEAR?

Transformers are an integral part of an electrical power network, as they ensure that the correct level of power is delivered to a site or customer. It is more efficient to transmit electricity from a power plant at a high voltage, but it must then be stepped down to a suitable low voltage for use in a factory or private network using a distribution transformer. Power transformers, by contrast, are used by large industrial users of energy and in transmission networks to deliver electricity at high voltage.

Industrial switchgear controls, protects and, where necessary, isolates electrical equipment such as transformers, ensuring that they can be operated and maintained safely and efficiently.

Power distribution equipment is suitable for remanufacturing as it meets the three key conditions:

- The equipment is high value, therefore the cost of labour and replacement parts for remanufacturing is lower than the cost of manufacturing new equipment;
- The technology is relatively mature and the evolution rate slow (more so for transformers than for switchgear); and
- The equipment can be designed to allow disassembly and repair.

REMANUFACTURING PROCESSES AND OPTIONS

End-of-life power distribution equipment arrives at Slaters Electricals to be used as input to the remanufacturing process; these inputs are called ‘core’. On arrival, the equipment is tested to ensure its suitability for remanufacturing. If it is suitable, the core is stripped and inspected, and damaged or unsuitable components are replaced. If necessary, moisture can be driven off by heating the equipment in ovens and damaged paint can be removed by sand blasting. The equipment will be repainted prior to testing and checking against the relevant standards. Finally, before units are shipped, they undergo internal quality control checks to ensure their performance is as good as new. During remanufacturing, approximately 85 per cent of the material in a transformer and 75 per cent of the material in a switchgear unit is retained, thereby avoiding the environmental impacts of disposal and recycling.

As power distribution equipment consists of energy-consuming products, there are inevitably trade-offs between the environmental impacts of different purchasing decisions: new equipment is likely to have improved energy efficiency during use because of the increasingly stringent legislative requirements, whereas using remanufactured equipment displaces the environmental impacts of disposal, recycling and new product manufacture. Therefore, the life cycle environmental impact of buying new equipment may, in some cases, be better than using remanufactured equipment. However, purchasing new equipment may not be an option for all customers, for example due to the higher capital costs and long lead times. Remanufacturing power distribution equipment has clear environmental advantages over less efficient second-hand equipment. It also provides the opportunity for equipment upgrade without the need to replace the whole system.

▼ **Table 1. The various options for equipment repair/replacement and associated lead times.**

Customer A: New build equipment	**Customer B: Expanding existing capacity**
Customer A is planning a new industrial facility that will require a transformer. All the other equipment will probably be new and the facility will take several months to construct. New transformers are manufactured to the latest international standards, including higher requirements for energy efficiency and reduced electrical losses in use. The lead time for purchasing a new transformer is up to three months.	Customer B has a bank of switchgear units, but would like to expand their capacity. Their units are no longer manufactured, but remanufactured switchgear and transformer units can be produced using core held in stock at Slaters. The lead time for remanufacturing a switchgear unit is one to four weeks.
Customer C: Failed equipment replacement	**Customer D: Failed equipment remanufacture**
Customer C has some existing transformer units, one of which has failed. Downtime is a significant problem, with the facility losing large amounts of money for each day the equipment is not operational. The failed transformer is a standard model and rating. The customer's core can be remanufactured in one to four weeks. Alternatively, Slaters holds a small stock of remanufactured units that it can supply to the customer within a few days.	Customer D has a failed transformer. Downtime is a significant problem, with the facility losing large amounts of money for each day the equipment is not operational. The failed transformer is repairable, but the facility must be kept operational while the transformer is fixed. Slaters holds a stock of remanufactured equipment for hire, which it can supply to the customer immediately (see **Figure 1**).

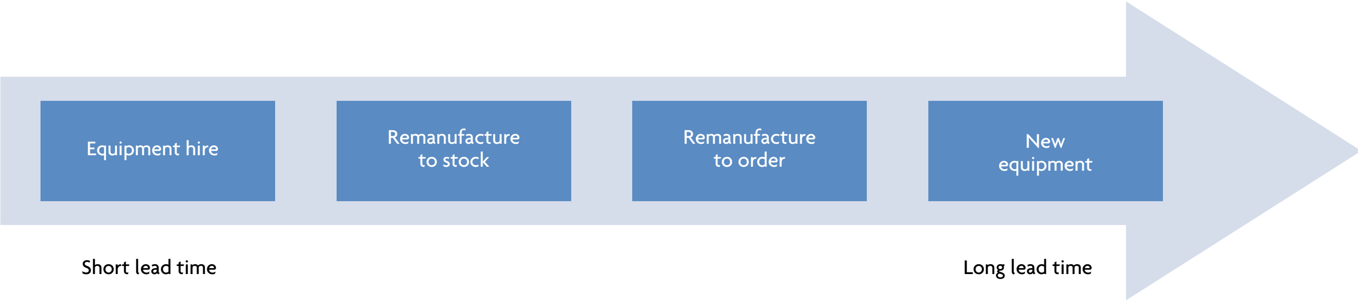
THE IMPACT OF LEAD TIMES

The length of time a customer is willing to wait for a piece of equipment to be repaired or replaced will vary greatly depending on the circumstances. Different scenarios faced by businesses requiring transformers are presented in **Table 1**.

Figure 2 summarises the range of products and services offered by Slaters Electricals and how these affect the lead time for their customers. For a business where availability and short lead times are key factors for many customers, remanufacturing offers a range of opportunities, not only to meet these customer needs, but also to use the workforce more efficiently. Remanufacturing hire equipment and remanufacturing of stock can be undertaken when there is less work remanufacturing to order.

“there are inevitably trade-offs between the environmental impacts of different purchasing decisions”

▲ **Figure 1. Warehouse containing stock of transformers, switchgear, hire fleet and spares at Slaters Electricals Ltd. (© Slaters Electrical Ltd, 2015)**



▲ **Figure 2. The relationship between business models and lead time.**

In summary, remanufacturing of power distribution equipment is a commercially and technically attractive business. Where buying new, more energy-efficient equipment is not an option, perhaps because of the higher capital costs or long lead times remanufacturing makes a strong business case. Also, purchasing or hiring remanufactured equipment certainly has environmental benefits over using older or second-hand equipment. For power distribution customers, availability and product lead time can be priority factors and in response, Slaters Electricals has developed a range of remanufacturing-based business models that both meet different customer needs and optimise their own day-to-day operations. These different business models are also valuable components of a circular economy. ES

Dr Rachel Waugh is a Technical Consultant at Oakdene Hollins, a research and consulting company working with business to support change towards more sustainable and less carbon-intensive products, processes, services and supply chains. Oakdene Hollins runs the Centre for Remanufacturing and Reuse, and Rachel recently led a successful Horizon2020 bid for a project to co-ordinate and support a European Remanufacturing Network.

Clare Adams is the Marketing Co-ordinator at Slaters Electricals Ltd, which specialises in the supply of power distribution equipment, services and support, and has been part of the electrical engineering industry since 1946. Clare has worked at Slaters since 2011, after completing her degree in graphic design at Northumbria University.

The circular economy in Japan

Dustin Benton and **Jonny Hazell** highlight what we could learn to reduce the costs and evironmental impacts of manufacturing.

The circular economy has become a hot topic for business leaders in Europe over the last three years. Spurred by a resource price shock following the financial crisis, many companies are exploring whether greater resource productivity can help them to maintain profitability in an era of volatile prices. Governments are catching up: despite the withdrawal in January of the EU's proposed circular economy legislation, the European Commission has pledged to reintroduce a more ambitious proposal before the year's end.

THREE GOOD REASONS

There are also at least three good environmental reasons to pursue the circular economy. First, existing recovery systems are suboptimal. For example, in mobile phones, only 17 of the 40 elements used in their manufacture are recovered at all, with the rest ending up in slag, even in the best recycling plants[1].

Second, from a lifecycle perspective, the environmental burden of products is shifting from use towards manufacturing. Around 75 per cent of carbon emissions from laptops, tablets and smartphones are generated before they are sold, and electric vehicles have roughly double the embodied carbon of internal combustion vehicles, (though their full lifecycle emissions are less)[2]. This means that keeping products in use for longer, or recovering and reusing them, is the best means of reducing environmental impacts.

Third, by decreasing the use of virgin materials, a circular economy can dramatically reduce emissions and negative environmental impacts of mining and refining. For example, producing 1 kg of gold releases 18,722 kg of CO_2 equivalent. Recycling is much less carbon intensive than mining: the embodied carbon in recycled aluminium – which, at 11.48 $kgCO_2/kg$

has much lower embodied emissions than gold – is typically one-tenth of that of virgin aluminium[3,4]. In addition, reuse or recycling avoids mining waste risks, like those relating to red mud in aluminium production. In 2010, a caustic waste reservoir containing red mud in Hungary catastrophically failed, flooding several villages and causing all life in the nearby Marcal river to be "extinguished"[5].

But despite the advantages, those seeking to reuse, remanufacture, recycle, or shift to services have found a range of barriers. Rather than reinventing the wheel, taking a close look at Japan's experience of pursuing a more circular economy can help to illustrate the sort of changes that might be required.

WHAT CAN WE LEARN FROM JAPAN?

Japanese recycling rates are extraordinary: the country recycles 98 per cent of its metals[6] and, in 2007, just five per cent of Japan's waste ended up in the ground, compared to 48 per cent for the UK in 2008. Japan's appliance recycling laws ensure that the great majority of electrical and electronic products are recycled, compared with 30–40 per cent[7] in Europe. Of these appliances, 74–89 per cent[6] of the materials they contain are recovered. Perhaps more significantly, many of these materials go back into the manufacture of the same type of product[8]. This is the 'closed-loop' holy grail of recycling, essential for a truly circular economy.

How has Japan managed to do so well? It has been trying to achieve a circular economy since 1991, a lot longer than anyone else, and is driven by a number of factors:

- First, it has high population density and limited landfill space, due in part to its volcanic and mountainous terrain; this forced the Japanese to find alternatives to landfill as early as the 1950s and to shift away from incineration in the 1990s, following concerns about dioxins (which can interfere with hormones, damage the immune system, cause reproductive and developmental problems, and cancer);
- Second, it is a major industrial producer but has very limited domestic metal and mineral resources, making remanufacturing and recycling attractive; it is hard to underplay the relevance of the importance of access to raw materials in Japan for public policy for the circular economy; and
- Third, Japanese business culture emphasises collaboration; the result is a comprehensive approach, both to measurement and to action.

MEASURING THE CIRCULAR ECONOMY

At a national level, Japan's belt-and-braces approach includes:

▲ **Figure 1. Japan has a high population density and limited landfill space (© Malgorzata Gajderowicz).**

- A resource productivity indicator measuring material use as a proportion of GDP;
- An indicator for cyclical use rate of materials in the economy, measured by the material reused as a proportion of total material used by the economy; and
- An output indicator, measuring how much waste is ultimately landfilled.

These indicators have associated targets. Japan supplements these with a host of sector-specific measurements, for which there are sometimes industry-specific targets. Finally, it also measures indicators of societal effort toward a circular economy, looking at the size of the market for rental and leasing of goods, the amount of reusable packaging sold, the number of local authorities that charge for residual waste collection, and even the sales of disposable chopsticks as a proxy for the proportion of the population that uses reusable chopsticks.

HOW JAPAN DESIGNED A CIRCULAR ECONOMY

When it comes to actually making the circular economy work, comprehensiveness and collaboration are at the heart of the Japanese system. The public plays a part by separating out recyclables, paying recycling fees directly and holding companies to account when necessary. Manufacturers do their bit[9] by using more recycled materials, and making longer-lasting products that are easier to repair and recycle.

The system has three key features:

- **Consumer-friendly collection:** the system for collecting old appliances for recycling is so comprehensive and easy to use that it is harder not to recycle them. Old appliances are collected by retailers either in store or when delivering a new appliance. For old IT equipment, the manufacturer can be requested to collect it by local authorities from the doorstep, or it can be taken to any post office to be returned to them. This is routine across Japan, making it well understood and widely used.
- **Consumers pay fees up front:** for electronics, the cost of transport and recovery is paid for at the point of purchase, meaning that the customer does not have any disincentive to participate when a product comes to the end of its life. Penalties for fly tipping are also stiff.
- **Recycling infrastructure is co-owned:** the law requires consortia of manufacturers to run disassembly plants, ensuring they directly benefit from recovering materials and parts. Companies therefore invest for the long term in recycling infrastructure. And because they own both manufacturing and recovery facilities, companies send product designers to disassembly factories to experience the frustrations of taking apart a poorly designed product. Some companies even put prototypes through the disassembly process to make sure they are easy to recover.

Japan's system is built on the assumption of collaboration, but the system also incentivises everyone to do the right thing. This model, neatly summarised as 'honesty, with incentives' shows that effective Japanese systems help to reinforce Japanese public spiritedness. A fascinating analysis[10] of the honesty and lack of looting following the Fukushima earthquake shows that this was the result of consistent and strong rewards for honesty and strict punishments for the dishonest, not just any innate qualities of the Japanese character. The result is that system does not just work well, it is also highly profitable: Japan's reuse and recycling economy was

CASE STUDY

worth £163 billion in 2007 (7.6 per cent of GDP) and employed 650,000 people[6].

The lessons for Europe are that governments need to help design circular systems, so that businesses can design circular products and services.

RECOVERING A NOVEL MATERIAL: NIMH CAR BATTERIES

Japan's very successful car industry is increasingly shifting to hybrid and electric vehicles, which require a supply of rare earth metals for their NiMH batteries. Rare earths are well dispersed throughout the Earth's crust but rarely occur in commercially viable quantities, so their production is associated with serious environmental risks: mining creates large, toxic, slightly radioactive ponds and the refining process requires the use of hydrochloric acid. Poor practices in China and Malaysia, for example, have been blamed for serious pollution of agricultural land and watercourses[11]. In contrast, lifecycle analysis of recycling neodymium, a rare earth, suggests it has a human toxicity score 80 per cent below that of mining[12].

Japan has always sought steady access to raw materials for industry, and thus in 1999 began recovering rare earths in car batteries as part of a wider effort to recover steel. However, until 2012, these rare earths were mixed into stainless steel, making them unavailable for use in new batteries. Chinese restrictions on rare earth exports, starting in 2010, provided a catalyst for the development of a battery-to-battery recycling process, which exemplifies how national government leadership, company collaboration, and effective reverse logistics combined to enable a novel material to be recovered.

Immediately after China announced the export restrictions on rare earths, the Japanese Ministry of Economy, Trade and Industry (METI) announced a grant programme to accelerate the commercialisation of rare earth recycling technologies. This grant enabled Honda and the Japan Metals and Chemicals Company (JMC), which had already cooperated on lab tests of technically effective though expensive means of recovering rare earths from car batteries, to invest in technical improvements to their process[13]. In brief, this involves extracting battery cells from Honda's battery packs, calcinating and pulverising the cells, separating iron scrap from the dust (which contains the rare earths), dissolving the dust in acid, and then electrolysing the rare earth salts that precipitate out of the acid. Because the rare earths are concentrated at the base of the battery electrodes, the key innovation was in optimising the pulverisation process to improve yields[14]. JMC and Honda now operate a recycling facility capable of recovering 400 tonnes of rare earths per year.

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The factors that enabled the new recycling process to be commercialised stretched across the supply chain:

- Government policy had supported recycling in industrial policy, in targeted innovation spending and in collection requirements;
- Corporations invested over a long period in collaborative research and design for recycling, long before resource security concerns prompted a push on rare earths; and
- Public expectations that recycling should be promoted underpinned both corporate and government drivers.

Of course what works in Japan cannot necessarily be copied wholesale, but we all can learn from the Japanese approach to creating a circular economy. ES

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The circular economy and the role of innovation

Julie Hill talks to **Jocelyn Blériot, Ella Jamsin** and **Mike Pitts** about their understanding of the circular economy, and the potential of new materials as catalysts for further positive change.

Jocelyn Blériot is a cofounder of the Ellen MacArthur Foundation. With a background in journalism and publishing, he has been instrumental in establishing the Foundation as a vibrant and highly visible global force dedicated to advancing and accelerating the concept of circular economy.

Ella Jamsin is the Ellen MacArthur Foundation's Research Manager, shaping research and analysis that informs the Foundation's work with businesses and regions. Her background is in management consulting and physics, including a PhD on black holes and higher dimensions.

Mike Pitts is Lead Specialist on Sustainability for Innovate UK (until recently the Technology Strategy Board), the government agency helping UK businesses to innovate more quickly. Mike is responsible for embedding sustainability across Innovate UK's £400 million investments. He is a chemist and sees circular economy as managing molecules and selling benefits rather than stuff.

The concept of the circular economy has gained traction over the past few decades as the pressure to use resources more effectively has grown. Meanwhile, scientists and designers have been demonstrating how the innovative application of new technologies can make industrial systems and processes more environmentally sustainable. Despite this progress, in order to bring about large-scale transformation, innovation needs to be a more routine part of daily life.

What do you think people understand by the 'circular economy'?

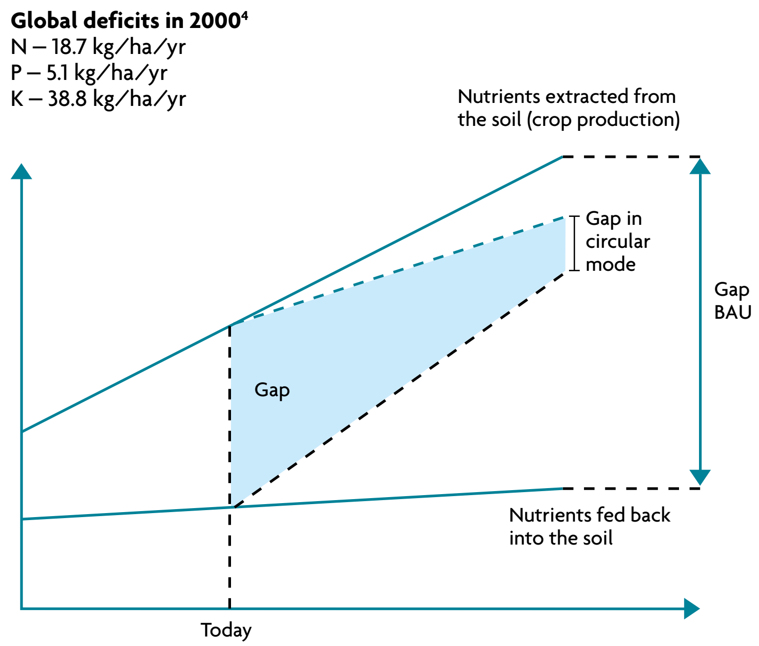
Mike The essence is simple: keep resources in use for longer. There are companies out there that understand the concept and want to change their businesses models completely, but I do get frustrated by how often the circular economy is reduced to recycling.

Jocelyn **Yes**, 'recycling 2.0' is too often the way people think about the circular economy, overlooking what we call the 'inner loops' of reuse, remanufacturing and remarketing. We should start with anything that preserves embodied energy – recycling is energy intensive and often not necessary. Most importantly we should think of it as an opportunity rather than a problem, and we highlight economic opportunity and space for creativity and innovation. Remanufacturing a product can save 75 per cent of the energy needed to make it from raw materials, thus reducing the atmospheric carbon emissions at the same time. Closing nutrient loops (for example by using sewage and manures in agriculture) means that in theory organic sources of fertiliser could contribute nearly 2.7 times the nutrients contained in today's total chemical fertilisers (see **Figure 1**)[1]. Those are big innovations with huge positive impacts.

What drives the circular economy from your perspective?

Mike Although the global economy is currently depressed, businesses believe that there is a long-term upward trend in the cost of raw materials because we have already used up the resources that are easy to extract. That also means that environmental challenges will increase, and that we need to decouple impacts from growth. The politics also becomes more difficult and supply chains become increasingly complex, with risks of supply interruptions and price volatility. As well as these very compelling reasons for resource efficiency and more circular economies, there is also the importance of changing business models for the benefit of the customer – how can we reduce impacts but improve the customer experience? Hour-by-hour car rental instead of private car ownership is a good example of how this can work.

Jocelyn and Ella We agree that the rising cost of energy and raw materials has been a major driver in kick-starting some companies' thought processes. For example, European car manufacturers have faced raw material and energy price increases of €500 million per year recently, which has wiped out a large proportion of their profit. This is a strong reason to think about flows



▲ **Figure 1. Illustrative graph (after Ellen MacArthur Foundation, 2013[1]) showing how circular economy principles could help regenerate soil to replenish natural capital by addressing nutrient imbalances in the absence of chemical fertiliser consumption. ('N' stands for nitrogen, 'P' stands for phosphorus and 'K' stands for potassium.)**

OPINION

and how to recapture materials. A product can become a material 'bank' for a company if it sells the service the product provides rather than thing itself, and consumer acceptance of this model is growing. The first wave of adoption of the circular economy was about economic constraints and access to new markets, before it became a buzz-word. But even in a slump people are conscious that there is a finite supply of resources, and that relying on efficiency strategies alone will only go so far.

> **"there is a critical lack of skills – green chemistry is supposed to be the future, but most chemists are being taught about oil-derived molecules"**

Where do novel materials fit in?

Mike To me, novel materials provide much-needed benefits: lower energy use, higher performance – lighter, stronger. We are getting better quality with each generation of new materials, too.

Ella One of my favourite examples is Ecovative packaging, a material that can replace polystyrene but is fully compostable because it is made from mushrooms grown on bio wastes[2]. Also wear2™, a yarn that dissolves under microwave radiation so that clothes can be disassembled. This is particularly good for anything with a corporate logo: pockets can now be removed for rebranding instead of scrapping the whole garment, as often happens now[3].

So, innovation can help with the circular economy, but there are potential challenges when novel materials are developed without recovery in mind. They can lead to further complexity, which hampers collection and reprocessing.

Jocelyn Yes, the proliferation of molecules and compounds on the market is a problem. We go for the cheap way of making molecules, not the smart way. If upstream design considerations and pathways for end of life are not taken into account, we undermine any possibility of a loop.

Mike We are always innovating, usually to get performance benefits, but the challenge is to avoid creating other problems along the way. Metal pouch packages, such as those used for pet food, are lightweight, so distribution costs less and their environmental impacts in use are less but they are difficult to recycle. What we need is superior performance across their life cycle. Products with complex mixtures, for instance with glues or hazardous materials, offer huge opportunities for improvement. The biodegradable bags that have been incentivised through the carrier bag charge are great as long as they are degraded in the right conditions. But we shouldn't be limiting our imagination to prospects for recycling. The right answer might be to make products last longer, or to reuse components of products rather than breaking them back down into basic materials.

Jocelyn I agree; we can't separate 'upstream' and 'downstream'. The circular economy is not about considering a material in isolation, but about how it can be repurposed or absorbed. If we want to use an analogy, living systems have a place for everything, and we have to ask if and where each new material fits. We don't want to create stuff that no one knows what to do with.

How do we resolve the challenge of the environmental impacts of new materials?

Jocelyn We've been working with Professor James Clark from the Green Chemistry Centre of Excellence at the University of York, assessing the use of new molecules. Looking at the huge potential of waste streams from orange juice production in Brazil, his team has been working on a process to extract lemonine from orange peel, which could displace synthetic lemonine from the market and remove the environmental impact of its manufacture. But there is a critical lack of skills – green chemistry is supposed to be the future, but most chemists are being taught about oil-derived molecules, as Professor Clark points out. That is why the Ellen McArthur Foundation is trying to influence higher-education agendas.

Mike We're not looking sufficiently at opportunities arising from waste products, or at extracting natural substances to replace materials that we use today. For instance, Piñatex™ is a leather substitute made from pineapple leaf waste (see **Figure 2**). There is clever molecular stuff going on in research, but let's not forget simple applications too. Nature spent millions of years evolving useful materials, so we should exploit their properties. Burning them shows lack of imagination – in effect, a thermodynamic crime.

What do you think your respective organisations can do to help resolve any dilemmas over novel materials?

Ella We work with research organisations and higher education to drive forward the circular economy. We also inform businesses and policy-makers about these challenges. On this topic, our most important initiative is Project MainStream with the World Economic Forum and McKinsey, focusing on collaborations to improve plastic packaging.

▲ **Figure 2. The upper of this shoe is made of pineapple leaf fibres (©Ananas Anam and Innovate UK).**

Mike Innovate UK is promoting projects that look across the entire supply and value chain – bringing together the people designing, making, using, selling and recovering materials. The benefits have to accrue to everyone otherwise innovation won't work. A good example of this is Axion's challenge on flexible, multilayer packaging. The project involved everyone, from plastic makers to brand owners, and the plastic makers are now happy to reformulate the plastic to help keep it in a closed loop. Innovate UK derisks projects by putting in money, but also works through to a practical end with all the partners.

Jocelyn Project MainStream is at heart of this question. The Ellen MacArthur Foundation brings together education, business, policy, insight and analysis to inform and initiate action.

Julie Thank you all. I wanted to have this conversation because of the common goals of the Ellen MacArthur Foundation and Innovate UK to bring different disciplines together, and to think more holistically about material and environmental challenges. Everyone in the conversation has emphasised the opportunities as well as the challenges. I get a strong sense of the emergence of new national competencies for the UK – in circular economy and systems thinking, novel materials and associated recovery processes, and products that meet consumers' needs while taking account of environmental limits. A rich future indeed! ES

Julie Hill is Chair of the Waste and Resources Action Programme (WRAP), an Associate of Green Alliance, and an independent Board Member for the Consumer Council for Water. She is also the author of '*The Secret Life of Stuff: A Manual for a New Material World* published by Vintage Books in 2011.

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