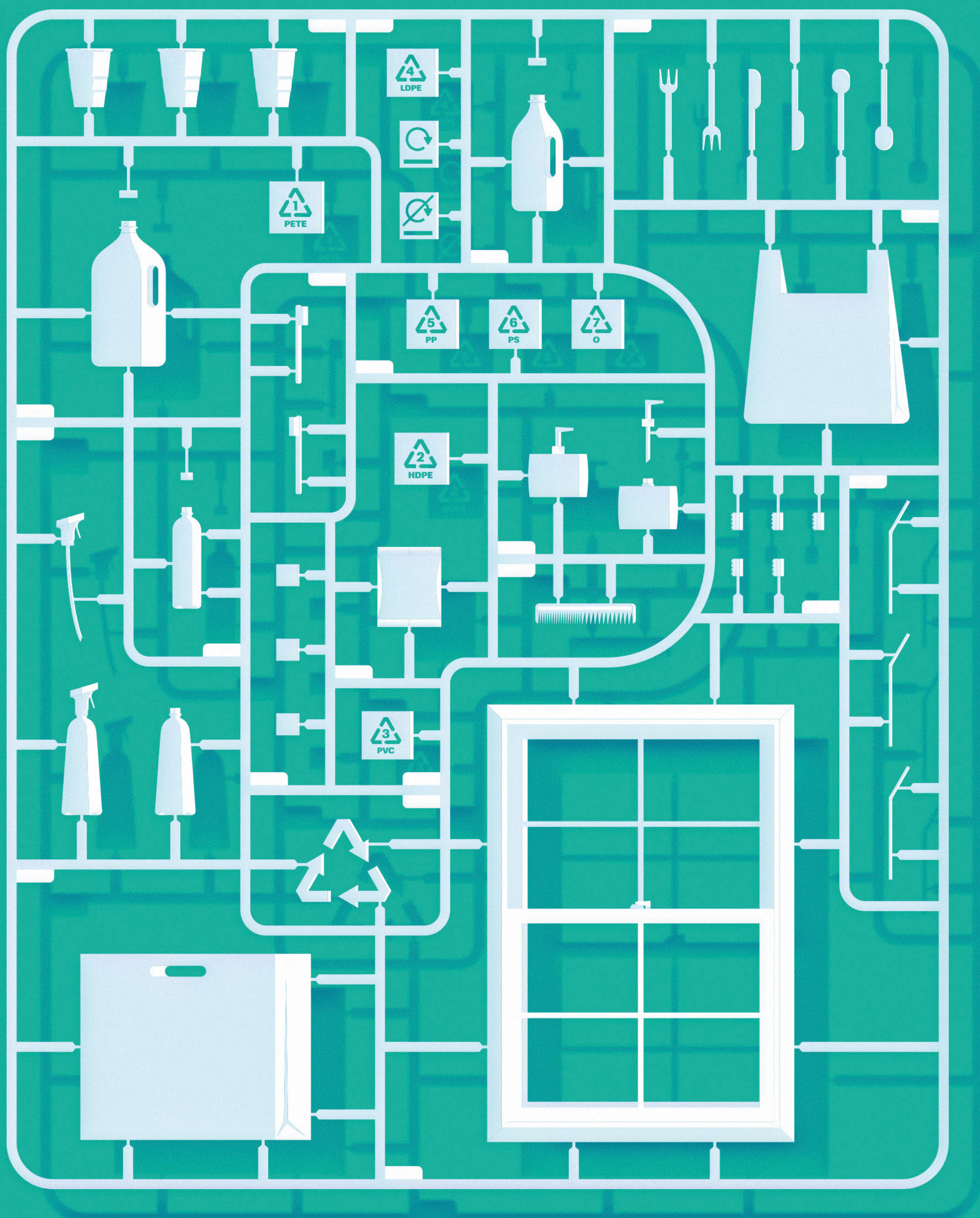
THE 'P' WORD



PLASTICS IN THE UK:
PRACTICAL AND PERVASIVE
... BUT PROBLEMATIC.

JONATHAN CULLEN
MICHAL DREWNIOK
ANDRÉ SERRENHO

SUMMARY

Plastics are ubiquitous in modern society, owing to their usefulness, durability and how cheap and easy they are to produce. This makes plastics both a blessing and a curse.

We manufacture a myriad of plastic materials, used in countless consumer products, which are highly valued by society. Everything from milk bottles to window frames, from sunglasses to face masks, contains plastic. Plastics are pervasive due to their practicality and profitability.

And yet, plastics have a problem. The making, use and disposal of plastics creates challenging pollution issues. Significant CO_{2e} (carbon dioxide equivalent) emissions are released across the life-cycle of plastic products and poor disposal means plastic makes its way into our waterways and oceans, creating serious environmental impacts.

Fixing this problem is not simple. Even finding good data, on the production, use, disposal and recycling of plastics is challenging.

This report tackles this data problem by mapping plastic flows through UK society, collating data from disparate sources on the production, use, disposal and recovery of plastics. With the resulting map of UK plastic flows, we can understand the latest trends in plastics use and identify opportunities for reducing the impacts of plastics in the future.

We found that the way we have been disposing of plastics plays a critical role in two serious environmental impacts: greenhouse gas emissions and plastic ocean pollution. These problems arise because plastics are not circular in the UK. Less than 3% of plastics consumed are made of UK recycled plastics, and the vast majority of waste ends up being incinerated, landfilled or exported. Without any action this problem will get worse, as we will generate more plastic waste in coming decades from all the products made of plastic that we have been accumulating.

Recycling more plastics in the UK could reduce incineration emissions, avoid mismanagement of exported waste and replace the need for the production of new plastics. However, current UK recycling capacity is only 12% of waste collected, and this is hampering the benefits recycling could provide.

There are several other actions we should take, such as reducing excessive use of plastic packaging, and reducing the range of polymers used in various products to improve recycling yields. These should be combined with improved practices in the petrochemical industry, and enhanced reuse and recycling of plastics to achieve a meaningful reduction in greenhouse gas emissions.

KEY MESSAGES

- The two most important environmental impacts of plastics are greenhouse gas emissions and ocean waste pollution. These problems are being aggravated by the way we have been disposing of plastics.
- Increasing recycling capacity in the UK could both reduce emissions and prevent ocean waste pollution. Our limited domestic recycling capacity leads to waste exports to countries with poor waste management practices.
- Action is urgently required to reduce the impacts of plastics. We must address the excess use of packaging, the variety of polymers used in similar products, practice in polymer production, and promoting reuse and recycling of plastics.

Jonathan M. Cullen,
Michal P. Drewniok,
André Cabrera Serrenho

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Design by New Rhythm Design

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UK Research and Innovation

PLASTICS ARE PRACTICAL

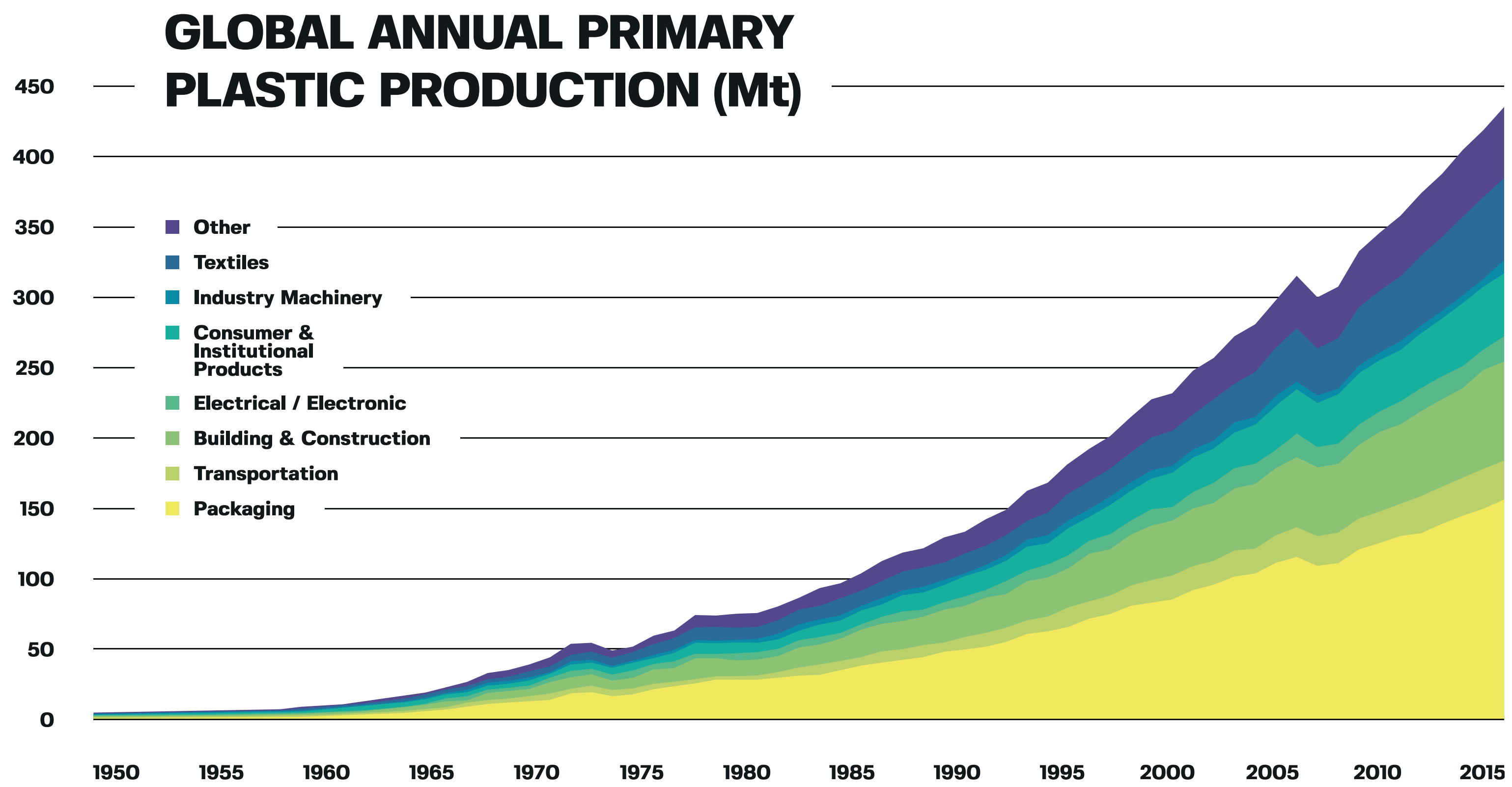


Fig.1 Global annual primary plastic production, by end-use, in Mt (million tonnes)

Plastics are a uniquely practical group of materials. They are strong, lightweight, flexible and durable. They can be shaped into almost any form. And they are cheap to make.

The unique properties have led to plastics being used in many thousands of products, bringing convenience and ease to our modern lives. Plastics find use in supermarkets, in packaging to reduce food waste, in hospitals, in protective clothing to limit infection, and in homes, in appliances, phones, wires and water pipes.

The attractiveness of plastics has led to rapid growth in the global plastics industry (Fig.1).

The first fully synthetic plastic, called Bakelite (phenylol-formaldehyde) was invented by Leo Baekeland in 1907. By 1941, more than 20 further plastic types (polymers) had been created and plastics began finding their way into products in housing, automotive, aviation, and electrical products.

However rapid growth in plastic production was only realised from 1950s onwards, with production increasing from 1.5 Mt (million tonnes) in 1950 to 438 Mt in 2017 (Fig.1). In fact, growth in plastic demand far outpaced global GDP over this period.

This has made plastics a profitable business over many decades.

Plastics are now used across a variety of sectors, including in packaging (36%), building and construction (16%) and the textiles sector (14%), as well as consumer and institutional products (13%).

The story of plastics over the last 75 years is one of insatiable growth driven by plastic's prized properties and low costs compared with other materials.

Demand for plastic, and other materials

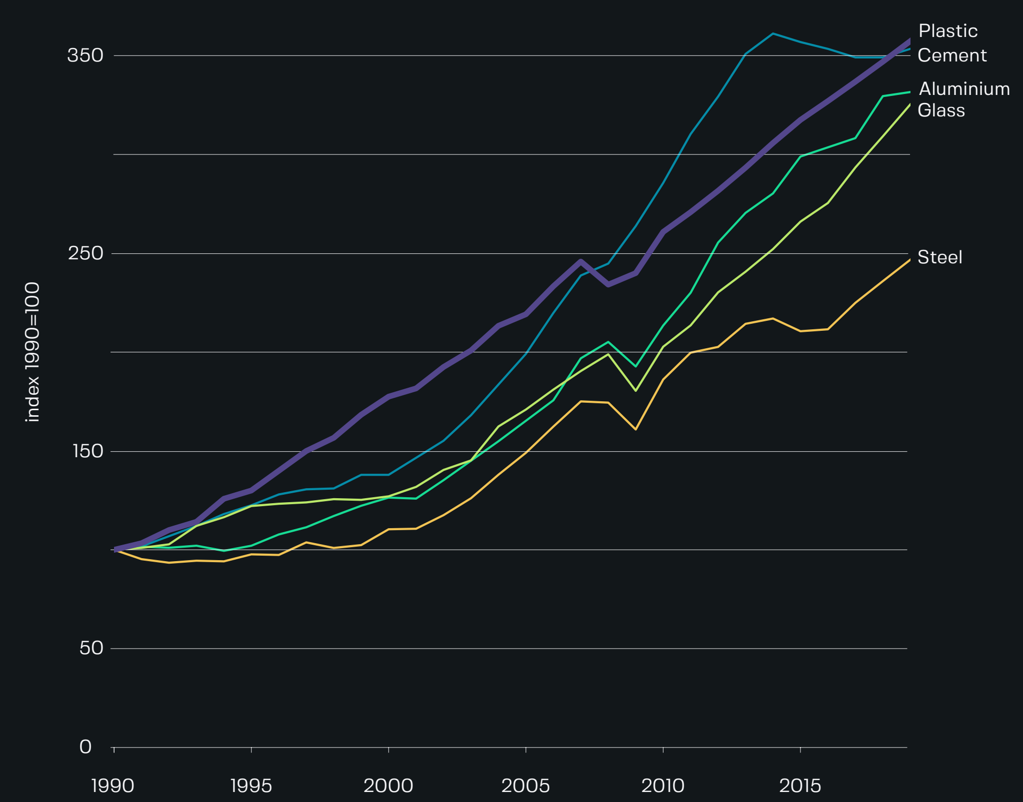


Fig.2 Demand for plastics is compared with steel, cement, aluminium and glass

From 1950 to 1990 global production of plastic increased sixty-fold (from 1.5 to 90 Mt), compared with four times for steel, nine times for glass, and twelve times for aluminium.

Growth has continued steadily from 1990 until today, with production increasing by three and a half times worldwide, as seen in Fig.2. During this period, plastic demand outpaced steel, glass and aluminium, and kept abreast with cement.

Much of this growth in demand has been driven by increasing populations and per capita wealth in developing economies around the world. In contrast, demand for plastic in the UK plateaued, with consumption remaining constant over the past decade, at about 6 Mt per year.

PLASTICS ARE PERVASIVE

There aren’t official statistics about plastics in the UK, and only disparate publications from PlasticsEurope and Waste & Resources Action Programme (WRAP) show us snapshots of a few stages along the supply chain of plastics. The data are still insufficient to tell us how much and which types of plastics are used every year, where they came from, on what products they are used and how they are disposed of. And knowing this is essential to identify what problems are being caused by plastics and what opportunities exist to mitigate them.

For this report, we had to conciliate available data on plastics with UK trade statistics in order to estimate the polymer composition in annual trade flows. By doing this, we were able to trace the flows of various polymers from production to transformation, use, and disposal.

The supply chains of plastics are complex, since each polymer and application is sourced in different ways. However, most of the plastics used in the UK were made in other countries, and most of them were imported as finished goods sold to final consumers. For this reason, the production of plastics in primary form in the UK supplies less than 20% of UK consumption.

Fig.3 shows that we use a huge variety of different polymers, and we even use several different polymers for similar types of product. However, this mixture of polymers causes problems when plastics are disposed of. Each polymer is recycled in a different way so the mixture has to be separated, requiring additional energy and emissions and degrading the polymer. Less pure recyclates also leads to the use of recycled plastics in lower value applications.

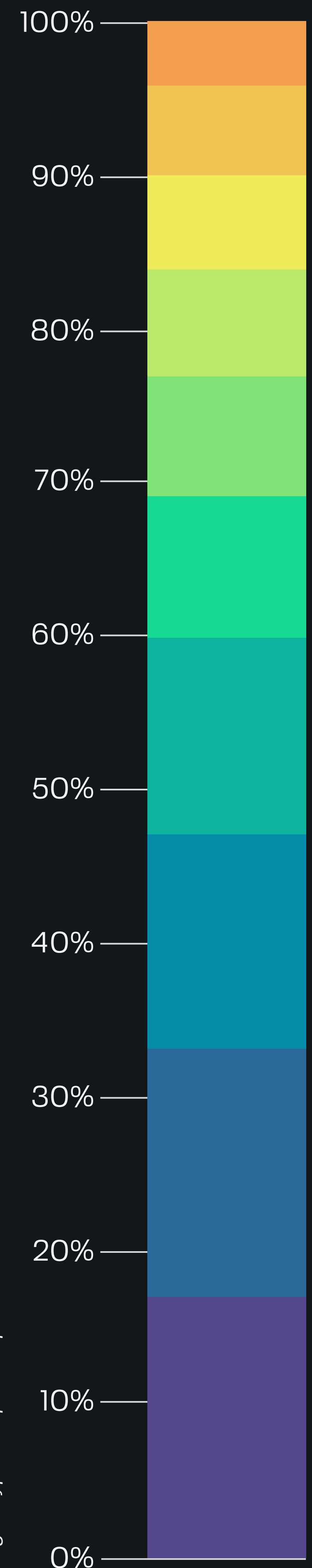


Fig.3 Types of plastic produced worldwide in 2017.

Plastics encompass a myriad of different materials and products, each with their own unique properties, uses and issues for recovery after use.

We tend to think of plastics as one uniform material. But plastic, unlike other materials such as steel, concrete and paper, encompasses numerous materials (or chemical formulations, as shown in Fig.3) and product configurations.

This makes the recovery of plastic material after use particularly challenging, as each chemical formulation needs to be treated separately.

Plastics are defined as: any of a group of synthetic or natural organic materials that may be shaped when soft and then hardened. This includes many types of resins, resinoids, polymers, cellulose derivatives, casein materials, and proteins, which can be extruded into shapes, used as coatings, drawn into fibres and woven.

Fig. 4 shows the flow of plastics through UK society, including the production, import and export of plastic materials visualised as a Sankey diagram.

POLYMER ABBREVIATIONS Polypropylene (PP), Low Density Polypropylene (LDPE), Polyester, Polyamide and Acrylic (PP&A), High Density Polyethylene (HDPE), Polyvinyl Chloride (PVC), Polyethylene Terephthalate (PET), Polyurethanes (PUR), Polystyrene (PS), Additives, Others.

PLASTIC FLOWS

UK 2017

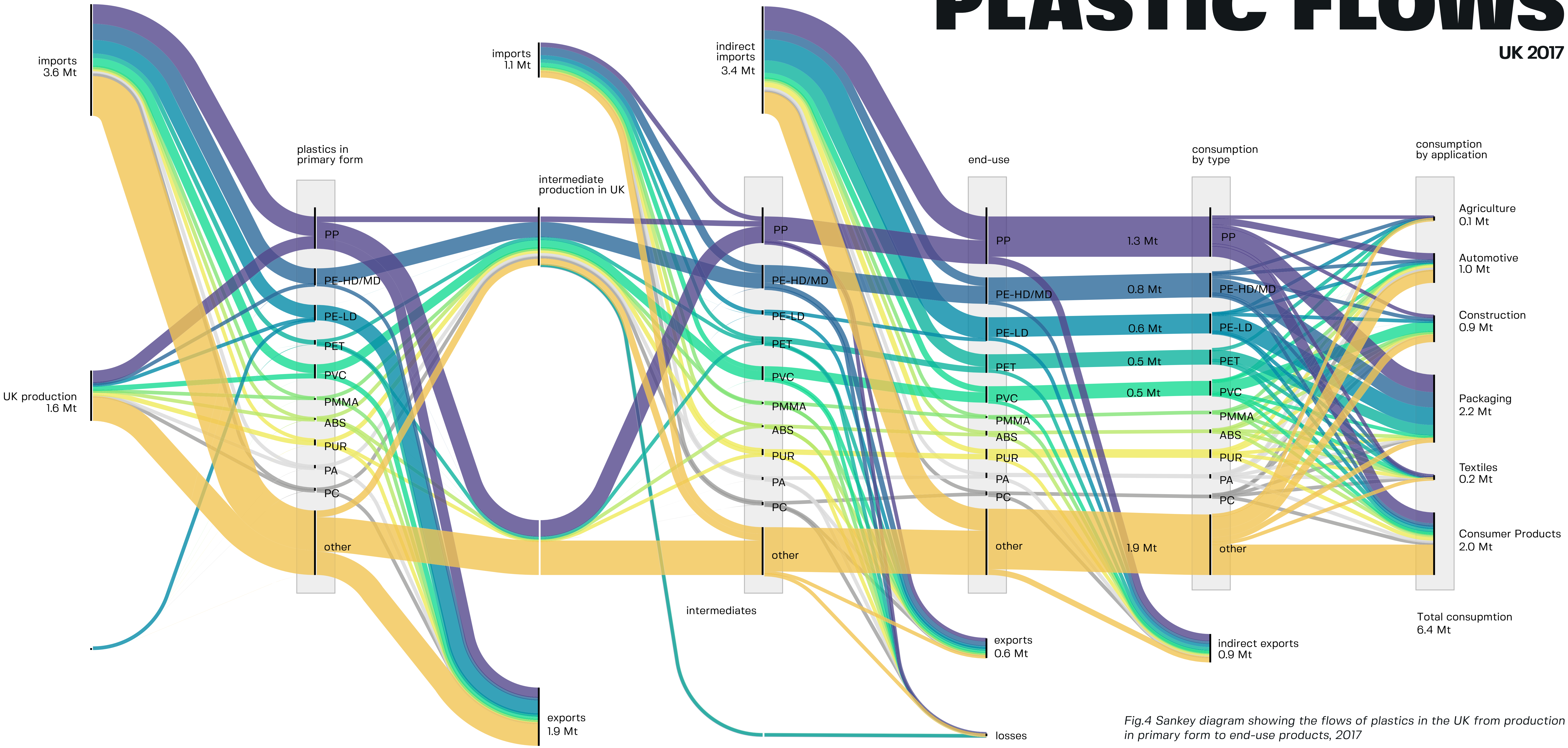


Fig.4 Sankey diagram showing the flows of plastics in the UK from production in primary form to end-use products, 2017

POLYMER ABBREVIATIONS
Standard Types: Polypropylene (PP), Medium/high density polyethylene (PE-HD/MD), Low density polyethylene (PE-LD), Polyethylene Terephthalate (PET), Polyvinyl-chloride (PVC), Poly methyl methacrylate (PMMA), Acrylonitrile Butadiene Styrene (ABS), Polyurethane (PUR), Polyamides (PA), Polycarbonate (PC), Other: Polystyrene (PS), Expanded polystyrene (EPS), Other thermoset (OTS), Other thermoplastics (OTP), Unsaturated polyester (PES), Silicone (S).

Our modern production processes, use and disposal of plastics create challenging pollution issues, from the release of CO_2 emissions to plastic waste found in waterways and oceans.

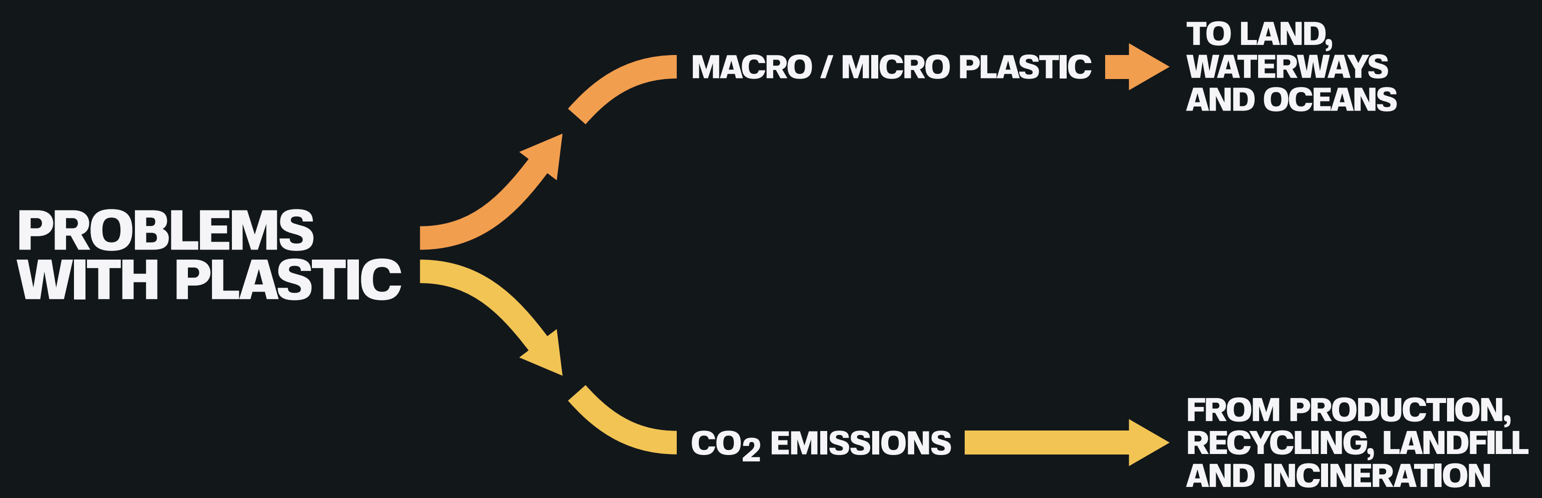


Fig.5 Plastic Pollution issues

PROBLEMS WITH PLASTIC

Plastics are useful, durable, cheap and easy to shape into products, and these desirable properties have led to spectacular growth in demand over the last century. Yet, their success is both a blessing and a curse. Plastics create challenging pollution issues, from the release of greenhouse gas emissions to plastic waste found in waterways and oceans.

The use of plastics in the UK generates 26 Mt CO_{2e}, every year, across the whole life cycle of plastic products. Production, both in the UK and overseas, accounts for 80% of these emissions. Burning plastics, which are derived from fossil fuels, creates 17% of emissions, with recycling and landfill contributing only 2.3% (Fig.6)

Single use plastics is the name given to products which are used only once or for a short period of time. Three such products—plastic cutlery, straws, stirrers and carriers bags—make up only a tiny fraction of CO_{2e} emissions from plastic. Yet these items currently dominate the UK's plastic waste strategy. There is a need to develop policies to address impacts from all products. The sheer number of plastic materials and products, means a variety of intervention strategies and polices will be needed.

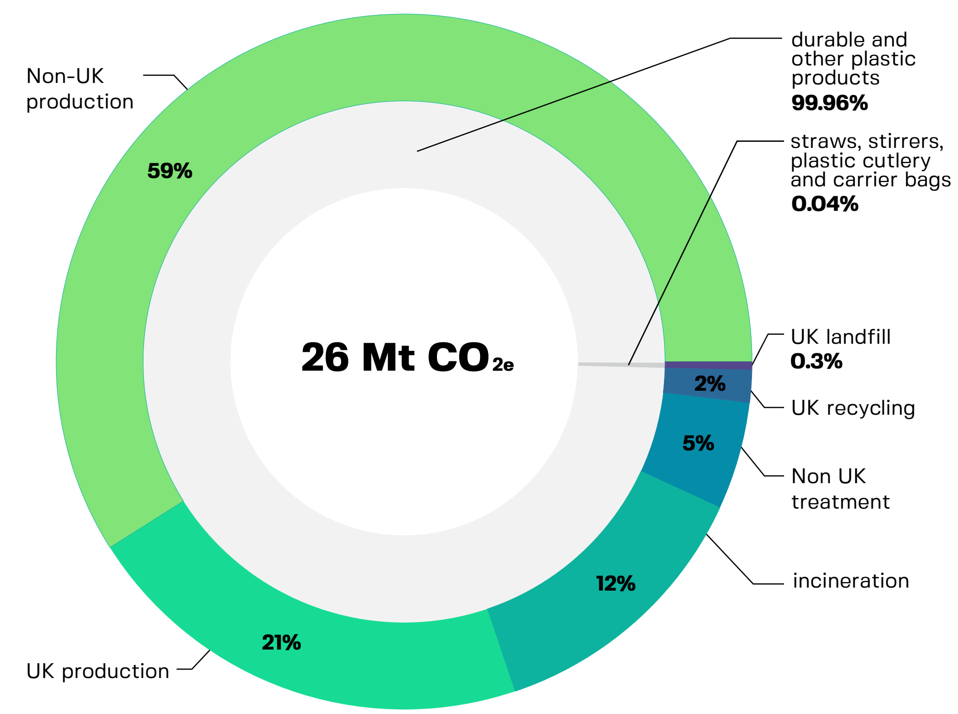


Fig.6 Whole life carbon emissions from UK plastic consumption

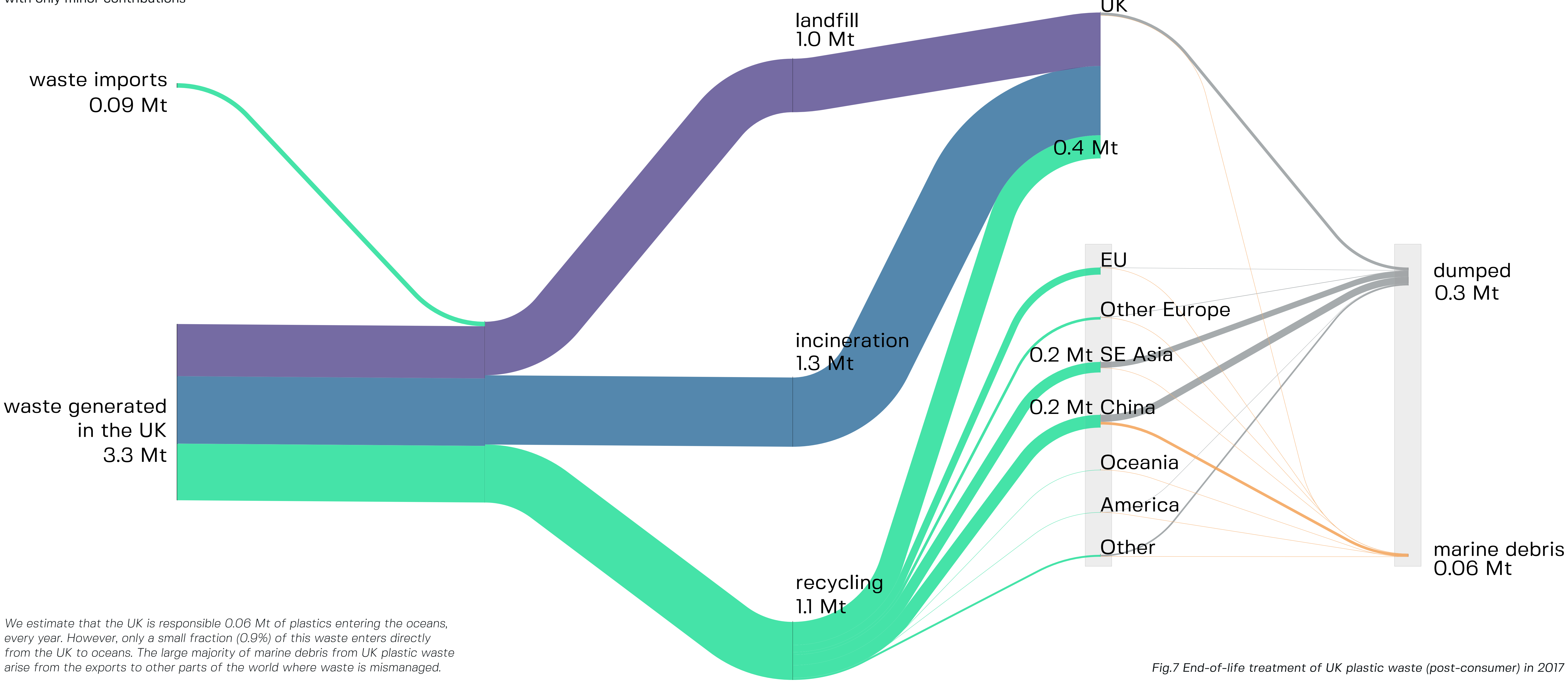
PLASTIC AT END OF LIFE

UK 2017

We have all seen images of the devastating effect plastics can cause in marine environments and across all ecosystems. These environmental impacts result directly from the mismanagement of plastics waste and the durability of plastic products. However, in countries with established waste collection systems, plastic waste rarely ends up in the oceans, with only minor contributions from consumer littering.

The UK reports 3.4 Mt of plastic waste arising in 2017–with roughly one third sent to landfill, one third to incineration, and one third for recycling (Fig. 7). The UK's limited recycling capacity meant only 0.4 Mt of plastic waste was recycled in the country. The remaining 0.7 Mt was exported to other countries, purportedly to be recycled. Yet, poor waste management practices in some of these destinations leads to waste being illegally dumped, resulting in plastic entering waterways and marine environments.

Fig.7 shows our best estimate of end-of-life flows of UK plastic and their destinations. We estimate that up to 2% of UK plastic waste (0.06 Mt) may end up in the oceans.



We estimate that the UK is responsible 0.06 Mt of plastics entering the oceans, every year. However, only a small fraction (0.9%) of this waste enters directly from the UK to oceans. The large majority of marine debris from UK plastic waste arise from the exports to other parts of the world where waste is mismanaged.

Fig.7 End-of-life treatment of UK plastic waste (post-consumer) in 2017

1 WHAT GOES IN MUST COME OUT

We saw in Fig.1 that global demand for plastic has grown at extraordinary rates. In fact, it is estimated that at some point, between 2017 and 2018, we produced the 10 billionth metric tonne of plastic (10,000 Mt). Of this, about 9,200 Mt was virgin plastic sourced almost exclusively from fossil fuels. Another 800 Mt was from recycled sources. Only 8% of all plastic material made to date has been from recycled content.

About 2,750 Mt of plastic material is locked up in plastic products which are still in use today. These products accumulate in society and are known as in-use stocks. Most of the remaining plastic produced, some 7,000 Mt over the course of history, has been discarded in landfills or nature (78%), incinerated (13%) or recycled (8%). The history of plastic production is a far cry from being anything like circular!

On an annual basis, the balance of plastics consumed and discarded is much closer. In 2017, humankind consumed 438 Mt of plastic products and created 328 Mt of waste (a through rate of 74% compared to the accumulated historical rate of 70%). The difference between plastics flowing into use, and out of use, comes about because some products remain in use for longer than a year (called durables), and this combined with growth in demand, means waste generation lags behind consumption. Therefore, the higher through rate today, compared to historically, reflects change in consumption patterns, and perhaps some shortening of product lifetimes (although it is difficult to unpick these two effects without better data.)

The balance of flows for the UK is quite different. In 2017, the UK consumed 6.4 Mt of plastic products (see Fig.4) and generated 3.3 Mt of waste plastic (Fig.7) with a through rate of only 51%. Given plastic consumption in the UK is relatively stable over time, this low through rate points to more durable plastic products accumulating as in-use stocks, with the generation of waste delayed.

The UK generated 3.4 Mt of plastic waste in 2017, with roughly a third going each to incineration, landfill and recycling (Fig.7). UK's recycling capacity is limited because with its tighter regulations and higher operating costs, plastic recycling in less economically viable. These conditions meant that only 0.4 Mt of the total 1.1 Mt sent for recycling, was processed locally. The remaining 0.7 Mt was sent overseas, yet, with little assurance that recycling was actually undertaken in these countries.

	Abbreviation	Full name	Recyclable	Ease of recycling
1	PETE (PET)	Polythylene Terephthalate	Yes	Easy
2	PE-HD/PE-MD	Medium/high density polyethylene	Yes	Easy
3	PVC	Polyvinyl-chloride	Yes (call recycler)	Difficult
4	PE-LD/PE-LDD	Low density polyethylene	Yes (call recycler)	Manageable
5	PP	Polypropylene	Yes / No	Easy
6	PS	Polystyrene	Yes / No	Difficult / Not Collected
	EPS	Expanded polystyrene	Yes	Difficult / Not Collected
7	PA	Polyamides	Yes	Manageable
	PC	Polycarbonate	Yes	Easy
	PMMA	Poly methyl methacrylate	Yes	Difficult
	PUR	Polyurethane	Yes	Manageable
	PES	Unsaturated polyester	Yes	Easy
	S	Silicone	Yes	Manageable
	OTP	Other thermoplastics	Yes / No	Various
ABS	ABS	Acrylonitrile Butadiene Styrene	Yes	Easy
	OTS	Other thermoset	No	Difficult

Table.1 Plastic recyclability in each.

ALMOST ALL PLASTICS CAN BE RECYCLED, BUT IN REALITY THEY ARE NOT

2 GRASPING AT STRAWS

Packaging accounted for a third of UK plastic consumption in 2017, with on average 46% of packaging waste being recycled. Among the packaging materials, the highest recycling rate was for plastic bottles (PET/HDPE) at 74%, while consumer plastic film was as low as 3.5%. Roughly two-thirds of plastic bottles are recycled in the UK, whereas all plastic film waste is currently either incinerated, landfilled or sent overseas, with no guarantee the waste is handled correctly. Very little recycling data is collected for the remaining two thirds of UK plastics consumption, which includes durable plastic products used in agriculture, automotive, construction, textiles and consumer products. Efforts to address the recycling of these products have been slow coming.

We suggest that the absence of comprehensive flow data across all UK plastic flows is a key barrier that holds back the development of policy and regulatory instruments for these larger slices of the market. Furthermore, UK regulatory bodies, in our view, have become fixated on specific single-use consumer products, which although highly visible, make up only small fractions of plastic demand and environmental impact.

PLASTIC STRAWS, DRINK STIRRERS AND COTTON BUDS

Much attention has been given to plastic straws, drink stirrers, and cotton buds, culminating in DEFRA imposing a ban in England from October 2020. These three items are highly visible to the public, are difficult to collect and recycle, and when released to the ocean, take centuries to degrade. Studies estimate that the UK consumes 4.7 billion plastic straws, 316 million plastic stirrers and 1.8 billion plastic-stemmed cotton buds each year. These are big numbers.

Yet, if we take plastic straws as an example, 4.7 billion straws equates to only 1.9 thousand tonnes of plastic, a small fraction (0.03%) of the UK's total plastic consumption (6.4 Mt). Of the 13 million tonnes of marine litter entering oceans each year, plastic straws make up just 1/4000th. Furthermore, litter collection studies on British beaches show that plastic straws and stirrers make up only 2–7% of the litter items, whereas cigarette filters comprise 20–80%. And popular alternatives to plastic straws, made from paper, are often coated with plastic for waterproofing, which contributes to micro-plastic waste and makes recycling difficult.

We are not suggesting that the environmental impacts from plastic straws, drink stirrers and cotton buds should be ignored. It is sometimes wise to reach for low hanging fruit first. But we question whether our limited capacity to push through regulatory change, however well-intentioned, should be spent on such a small prize.

TAKE–AWAY TRAYS

The UK consumes 63 thousand tonnes of polystyrene (PS) and expanded polystyrene (EPS) packaging, with 90% used for plastic pots, tubes and trays (PPTs). These short lasting, single use packaging items are commonly used for keeping food hot or cold and preventing contamination. The humble take-away tray is a ubiquitous example.

Both styrene-based polymers are easily recycled and yet the UK has only the capacity to recycle 2% of the UKs styrene-based waste. PS and EPS packaging are not separated for kerbside collection and are therefore either landfilled or incinerated. On a simple mass basis, PS and EPS packaging is 30 times more important than plastic straws and focusing regulatory action to address the lack of recycling facilities of PS and EPS, for example, might be a more effective use of time and effort.

3 OCEAN WASTE POLLUTION

MACROPLASTICS

Every year, as much as 13 Mt of plastic waste enters the oceans. This is more than twice the annual consumption of plastics in the UK. Most plastic waste enters the ocean due to inadequate poor waste management systems. In 2010 most plastic marine debris came from China and SE Asian countries.

In 2018, China stopped importing several types of plastic waste, while most developed countries, such as the UK, produce more plastic waste than they can process domestically, and as a result must export plastic waste to other countries. Yet, these countries will often have high rates of waste mismanagement, with plastic waste being dumped in open landfills, being burned or finding its way to rivers and oceans.

OCEAN WASTE IS A BIG ISSUE, AND THE UK CONTRIBUTES ABOUT 1% OF MACROPLASTIC OCEAN WASTE.

MICROPLASTICS

Microplastics are a significant source of plastic pollution and environmental impact. These are plastic particles smaller than 5 mm and they occur in the environment as either primary or secondary microplastics.

Primary microplastics are small plastic particles deliberately manufactured for abrasives or cosmetics, which later find their way to the environment.

Secondary microplastics result from the mechanical degradation of larger plastic particles, e.g. by washing garments made of plastic fibres or from the natural erosion of plastic waste.

Pollutants, such as aromatic hydrocarbons (PAHs) and heavy metals tend to adhere to the surfaces of microplastics and can accumulate in food chains.

About 0.95Mt of microplastics make their way into the global marine environment every year, with 28% from vehicle tyre dust, 24% from marine, road and building paint, 24% from spills of pellets used in manufacturing, 20% from textiles and 4% from cosmetics.

There are no simple options for preventing microplastics entering the ocean, but improving plastic waste management, making paint and textiles more durable, and limiting car travel, all help.

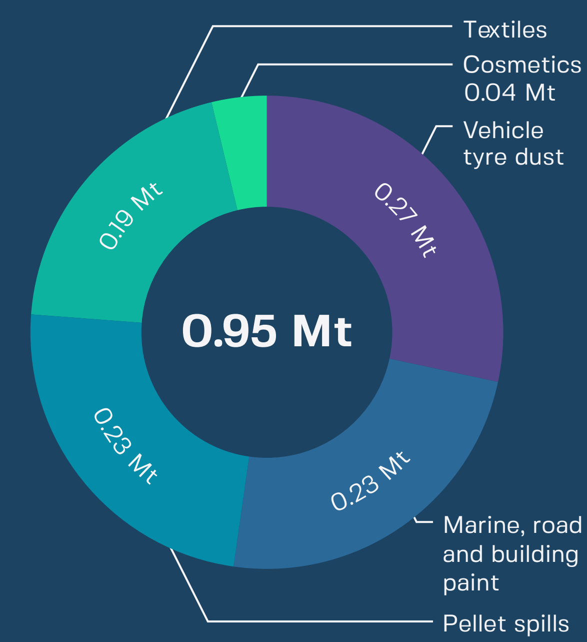


Fig.8 Global annual microplastics waste in the marine environment.

PROJECTING FUTURE FLOWS

UK 2017–2050

If we carry on the current patterns of use of plastics, we will have to deal with approximately 6 Mt of plastic waste every year in the UK. It is technically possible to recycle all man-made polymers, but not in the UK. Some polymers are even excluded from kerbside collection. Our limited capacity to recycle plastics in the UK—currently only approximately 400 kt (thousand tonnes) per year—means that most of what is labelled as recycled is instead exported.

Since the UK exports most of its plastic waste, it is simply not possible to create a domestic circular plastic economy (Fig. 9). Nor is the UK's use of plastic circular in a global sense, with less than 1% of UK plastic demand being supplied with recyclates.

Recent policies have targeted reductions of single-use plastics (such as drinking straws which make up only 0.04% of plastics used in the UK.) However, increasing UK recycling capacity across all products could prevent mismanagement of plastic waste and improve material circularity. As a result, this would reduce the need to produce new plastics for the UK every year, and thus avoid the emissions of producing them.

Recyclability currently depends also on the levels of purity of the various polymers. Yet, a wide variety of different polymers for the same or similar applications is a challenge for polymer separation and contributes to low recycling yields. Reducing the number of polymers used in plastic products would allow plastic waste to be recycled more effectively, thus reducing demand for new plastics.

THE UK HAS 42 MILLION TONNES OF PLASTIC PRODUCTS IN USE

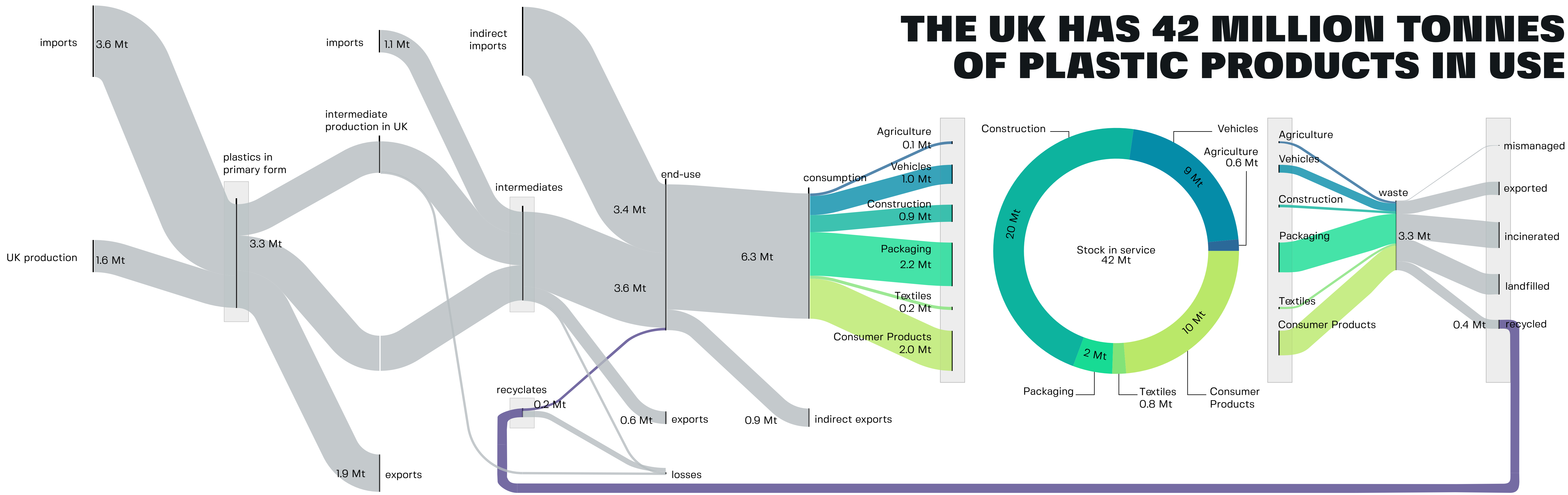


Fig.9 Sankey diagram showing the small fraction of recycled plastic waste that would be made if UK kept current capacity — almost no circularity

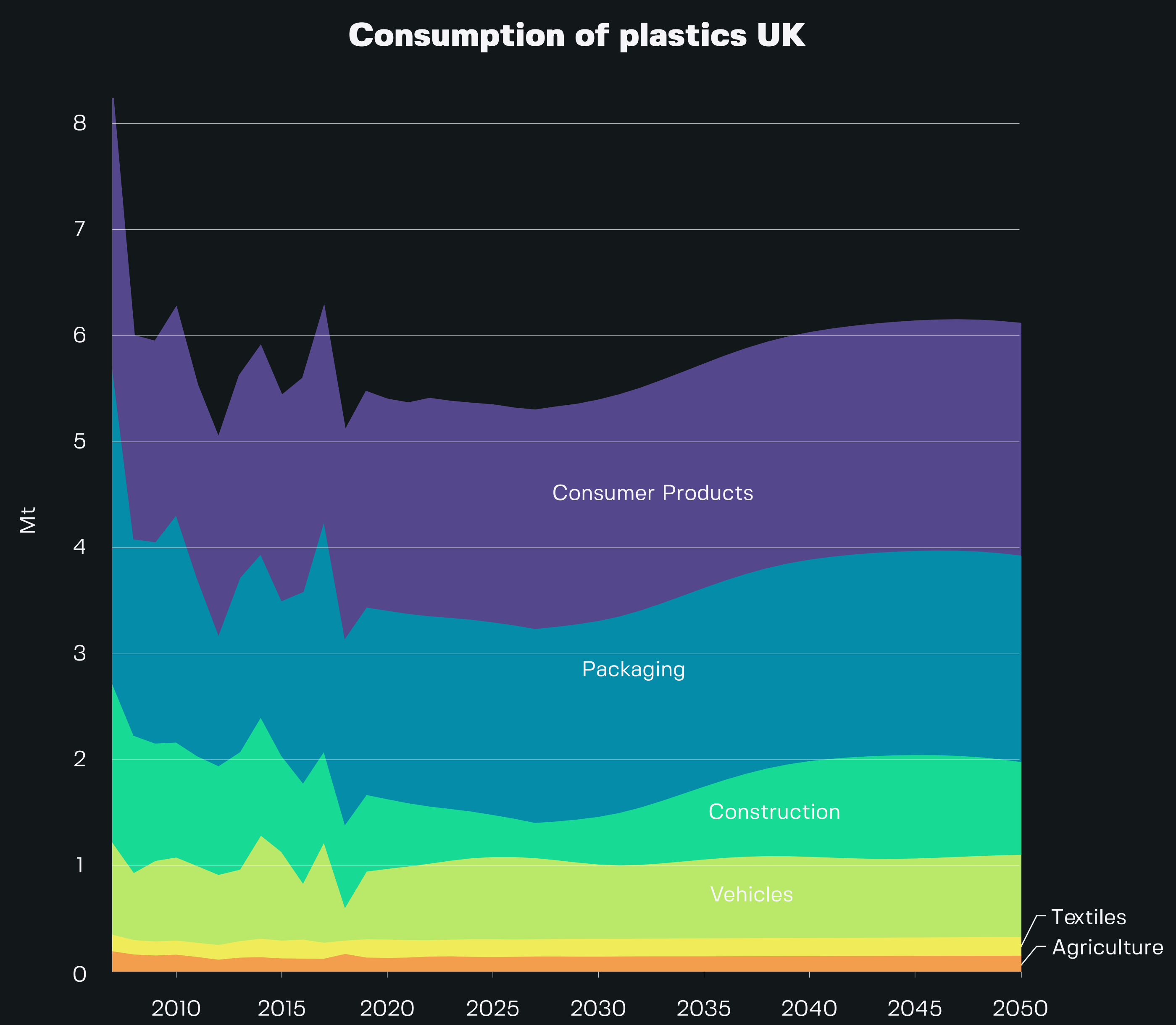


Fig.10 Anticipated demand by application, 2018–2050.

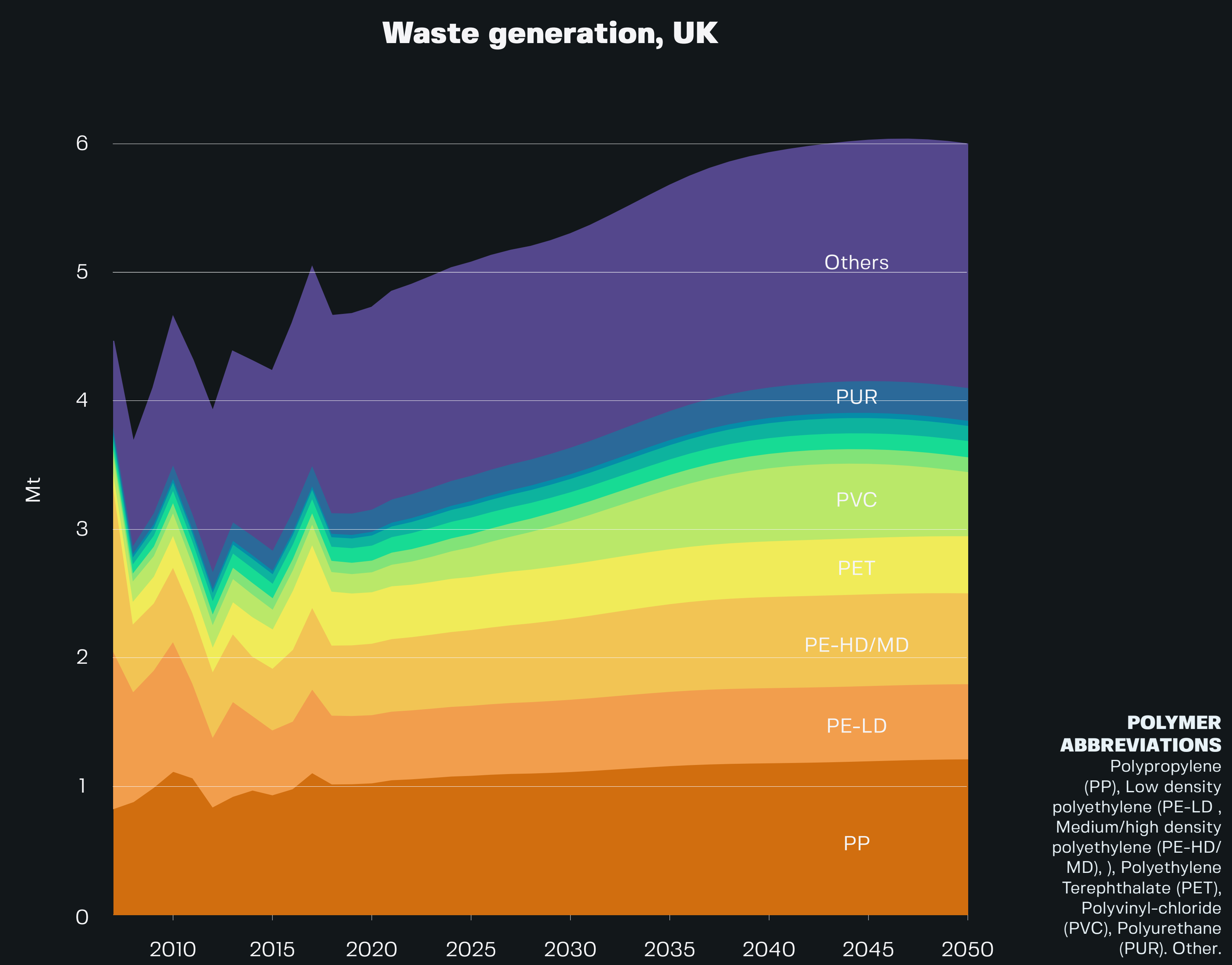


Fig.11 Anticipated waste generated by polymer, 2018–2050.

UK demand for plastics is expected to remain constant over the next 30 years.

Our work on mapping the flows of plastics over time allows us to estimate the stocks of plastics currently in service. Since the various products made of plastics have different lifespans, plastic disposal happens at different points in time. Luckily, if we are able to know how much plastic is currently being used, we can estimate how much waste will be generated in the future.

Plastic packaging accounts for 40% of annual consumption of plastics in the UK. And since these plastics are short-lived, they end up being disposed within one year of consumption. However, we found that almost half of plastics currently in use are in construction, and these products often last for decades. We have built a backlog of plastic in construction which will only become available as waste over the coming decades. As a result, we estimate that if we keep our patterns of use of plastics, we will end up generating approximately 50% more waste by 2050 than we are producing now.

This is both a problem and an opportunity. Currently our limited capacity to recycle plastics in the UK (about 400 kt per year) means that most ‘recycled’ plastic is exported, with no guarantee that it is recycled properly. Yet, by increasing recycling capacity in the UK, we could process the growing volumes of plastic waste, and avoid the need to produce so much new plastic.

Solutions to address plastic pollution exist, but many of the technologies are not available at scale and may be linked to unintended consequences.

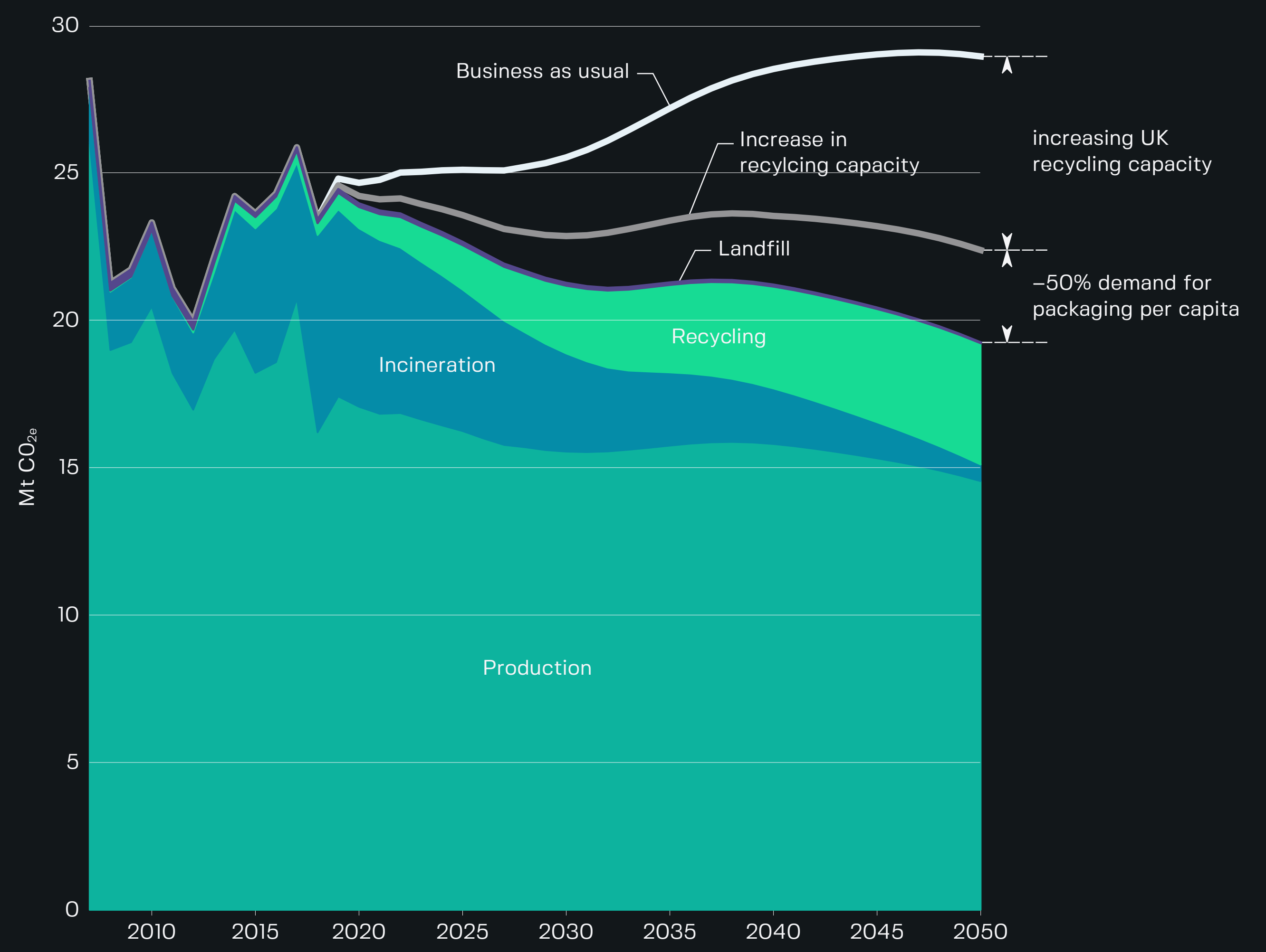


Fig.12 UK plastics emissions/waste for the following scenarios: Incineration, Recycling, Production and Landfill.

POSSIBLE PATHWAYS FORWARD

Increasing recycling capacity in the UK could avoid mismanagement of exported waste and avoid production of virgin plastics. This would reduce plastics emissions, as shown in Fig.12. This figure also shows the emissions savings achieved by halving the demand for packaging per capita. Packaging has high throughput and very short lifetime, so a reduction in demand would rapidly reduce production emissions and the environmental impact of plastic waste management. Preventing food waste, a significant source of emissions itself, has the added benefit of reducing packing waste. However, almost 40% of plastics consumed annually are not seen by final consumers. These are mostly packaging used in B2B transactions, and so there is a meaningful opportunity to reduce this type of packaging.

However, the potential for emissions savings of the measures above combined is still modest (Fig.12), reducing emissions from current 26 Mt CO_{2e} to 20 Mt CO_{2e} by 2050. This is because even with maximised recycling capacity, recycling yield losses are very high, due to polymer mixing in waste streams and the limitations of the mechanical recycling processes. As a result, a substantial increase in recycling capacity wouldn't lead to a meaningful reduction in the production of new polymers and their associated emissions. Further savings will have to come from a combination of other strategies, such as:

CHEMICAL RECYCLING

Plastics recycling is currently done using mechanical recycling processes, which processes plastic waste into the secondary products without significant changes to their chemical structure. However, using more energy it is possible to reduce the polymers in plastic waste to basic molecules that can be used to synthesise new plastics. This recycling would enable higher grades of recycled plastics, increasing recycling yields. Chemical recycling is still not available at commercial scale. But if powered with zero-carbon energy sources, chemical recycling could enable the replacement of more new plastics production, and thus lead to substantial emissions savings.

BIOPLASTICS

Bioplastics are produced from biomass feedstock instead of fossil fuels. As a result, these plastics have much lower emissions generated during production. However, due to their greater biodegradability, most of these plastics have a higher emissions at the end-of-life, particularly if landfilled or composed. This is an area of active research and there is an opportunity for innovation in the production of non-fossil fuel-based plastics with better life-cycle emissions performance than conventional plastics.

REUSE AND DESIGN

Better product designs that foster longer lives and reusability can promote plastics demand reduction, and allow simpler separation at end-of-life.

INNOVATION IN THE PETROCHEMICAL INDUSTRY

The chemical and petrochemical industry is one of the largest global industrial sources of emissions. An important source of emissions in this sector is the result of CO_2 generated as a product of chemical reactions required to make some of the precursor molecules used in plastic production. There are opportunities to explore innovative methods to avoid these emissions and to deploy carbon-capture processes in the petrochemical industry.

PLASTIC PACKAGING FILM

Plastic packaging film is commonly used for perishable foods, to limit the food's contact with oxygen. In 2017, the UK consumed 395 kt of plastic film, but due to the lack of recycling capacity in the UK and low economic value of this type of waste, only 4% of waste arising were collected for recycling. The remaining was either landfilled, incinerated or exported.

PLASTIC FOOD PACKAGING

Food waste is a much larger contributor to climate change than the plastic used for packaging food. In fact, WRAP estimated the food waste in the UK generated 25 $MtCO_{2e}$ last year, which is almost exactly the same amount created by whole life emissions for all plastic products consumed (26 $MtCO_{2e}$). Overall, some 9.5 Mt of food, out of a total 44.5 Mt purchased, is wasted from UK households and businesses. The largest share of food waste from households are fresh vegetables & salad (1.85 Mt), sauces, pasta, rice, cakes, desserts, oils, fats, confectionery (1.06 Mt), drinks (0.99 Mt), bakery (0.73 Mt) and meals (0.59 Mt). We calculate that reducing this food waste to zero, could in turn lead to a 20% reduction in plastic film waste and a 5% reduction in plastic bottles, used to for packaging the food.

Refrigeration in the home is vitally important for maintaining freshness and extending the storage-life of food and drinks. Food stored in the fridge will typically stay fresh for 7–14 days longer than food stored at a room temperature of 22°C. Storing fresh produce in a plastic in the fridge can help to retain moisture and freshness, Yet, only lemons and peppers, from a selection of 17 fruit and vegetables types, showed any significant improvement (of more than three days) in storage-life when refrigerated inside a plastic bag. The other 15 fruit and vegetables remained just as fresh when stored without packaging.

PROBING NEW SOLUTIONS

RESEARCH HIGHLIGHTS FROM CIRPLAS, THE CAMBRIDGE CENTRE FOR CIRCULAR ECONOMY APPROACHES TO PLASTIC WASTE

KHALED SOUFANI

"CIRCULARITY BY DESIGN – CIRCULAR BUSINESS MODELS"

Today's cradle-to-grave economy sees around 80 per cent of plastic landfilled, incinerated or lost into the natural environment. It is argued by some that we are using resources 50 per cent faster than can be replenished. It has also been said that by 2030 we will require the natural resources supply of two Earths, and by 2050, three. We need a circular economy with re-use of products and recycling of embedded materials into new products.

Cambridgeshire-based packaging company Charpak believes it is the first in the UK to adopt a 'localised circular economy' in which local plastic waste is collected, re-processed and re-manufactured into new packaging. The company has been chosen by Prof Soufani's team as a case study to look at the viability of a circular business model. The translation of the circular economy into business models that eliminate plastic waste is relatively unexplored and so there's little guidance for practitioners who would like to adopt such a model. The researchers are addressing this gap by mapping how Charpak has approached the circular economy and by estimating the impact of their efforts.

Before any company will look at embedding circularity, they are going to ask a very simple question: how will it impact on me financially? Communities, companies and governing bodies need to see practical business cases and models in action.

"Minimising plastic leaking into our environment is a responsibility we take very seriously, so we must ensure plastic becomes a resource and not waste," says Charpak Managing Director Paul Smith. "Why transport essential plastics resources nationwide, or overseas, and risk ocean plastics when the plastic resource is required for manufacture and re-manufacture within the UK? We want to be part of the solution."

We need to shift from a culture of mass consumption and waste towards renewability, dematerialisation and reduced resource loss. Our need to reduce, remake and recycle is a continuous journey towards circularity that will define our relationship with the planet forever.

BRIGITTE STEGER

"IS CHARGING PEOPLE FOR PLASTIC BAGS ENOUGH?"

If the UK's experience is anything to go by, the answer appears to be a resounding 'yes'. The 2015 introduction of a 5p minimum charge for plastic bags caused consumption to drop by about 90%. But attitudes and habits vary around the world, as social scientists in the CirPlas Team at the University of Cambridge – Dr Teresa Perez, Dr Patrick O'Hare and Dr Brigitte Steger – discover. Uruguay's 2019 law introduced a 4c charge and stipulated that bags be biodegradable. Consumers broadly welcomed the idea. Ramón had been refusing bags for years even though people thought he was strange. Daniela had re-used carrier bags as rubbish bags and now had to buy the latter but she knew this was better for the environment. Yet controversies remain, despite an amazing

80% reduction. For example, on biodegradability, Uruguay copied an EU definition which failed to consider lack of infrastructure and disintegration in marine environments. One of the local solutions: a bag made of starch that dissolves in the sea to help protect Uruguay's long coastline.

'Plastic is easy to throw away', Sayuri in Tokyo comments, referring to both practical and moral considerations. Plastic bags simply go into general waste for incineration, free of charge. This changes in 2020: shops must charge a minimum of 1yen. However, providing bags is intrinsic to Japanese customer service: 'We travelled to France. In the supermarket they asked for money for the bag! What a rip-off,' the Tairas recall. While Mrs Taira now uses her own bags when shopping, resistance to giving and receiving purchases 'naked' lives on.

In South Africa, a 43c plastic bag levy was introduced in 2003 but then quickly reduced after pressure from the plastic industry. In 2020 the government announced an increase from 12c to 25c. Shoppers accumulate bags but not necessarily to use for repeated future supermarket visits. Lele, a resident in Cape Town, said "If I am a customer, [and] you say to me 'do you want a plastic bag?' I will always say 'yes' even if I have one. " He explained that he tends to re-use bags only once, for example, as bin liners. Hence, the plastic bag levy has not had the anticipated impact on reducing plastic bag consumption.

Charging for plastic bags is not a panacea. While saving money is a strong motive to reduce single-use plastic waste, trust in the infrastructure and recognition that one is 'doing the right thing' are equally important.

ERWIN REISNER

"SUNLIGHT-DRIVEN CONVERSION OF PLASTICS WASTE INTO HYDROGEN FUEL"

8 million tonnes of plastic flow into the ocean each year, an environmental crisis that is expected to worsen as plastic use for personal protective equipment sky-rockets during the COVID-19 pandemic. Research in the Reisner Lab at the University of Cambridge has established a chemical recycling method powered by sunlight to mitigate plastic waste and generate green hydrogen fuel. In this "photoreforming" process, a special material called a photocatalyst harvests solar energy to break apart plastic waste into pure hydrogen gas and useful chemicals. The key benefits of photoreforming include its simplicity, use of renewable solar energy, operation at room temperature and compatibility with non-recyclable waste such as microplastics and food-contaminated plastic.

The Reisner Lab's work on this topic has recently been highlighted in the Sunday Times as one of 11 great ideas from British universities that could change the world (26th April 2020 edition). The technology is protected by a patent (PCT WO2019/229255), developed with the support of the university tech-transfer office Cambridge Enterprise and secured university as well as industrial support (OMV Group) for up-scaling and development. A Translational Prize of the EPSRC Centre for Functional and Sustainable Nano has recently been awarded to this project for development towards commercialisation.

With further research advances, photoreforming could contribute to a carbon-neutral society by simultaneously generating clean hydrogen fuel, mitigating waste and producing bulk chemicals for a sustainable chemical industry

ADRIAN FISHER

"TECHNOLOGICAL PLATFORMS FOR HARNESSING ELECTRICITY FROM WASTE PLASTICS"

One future sustainable technological approach which is not widely commercially available yet falls under the engineering umbrella of bioelectrochemical systems (BESs). BESs are typically electrochemical devices that employ biological materials, termed as biocatalysts, to generate electricity as well as value-added products. These systems rely on the ability of certain microbes or other biological substrates to export electrons outside of their cells, a mechanism referred to as exoelectrogenesis. The electrons can, then, be harvested for reductive power and chemical products. In these electrochemical systems, a low redox potential of an oxidation reaction at the anode and a high redox potential of a reduction reaction at the cathode create a potential difference. Electroneutrality is guaranteed by the movement of ions, usually hydrogen ions, through an ion-permeable medium or membrane.

In this project we design, develop and build a series of candidate reactors which can accommodate bacteria or other biologically active materials which are reported to degrade plastics. We use the reactors to study candidate biological substrates and as an outreach platform for inclusive education. Here we report the design approach and inclusive education activities which were carried out with partner organisations both in the UK and internationally

In this investigation we have applied our electrochemical design engineering approaches to develop optimised reactor designs for waste utilisation and conversion to electrical energy. These are based on the development of rigorous quantitative experiment-based models for multi-scale bioelectrochemical reactor systems. When we have a system of representative equations and/or a set of systematic data from experiments, the question arises whether the measurements allow for reliable identification of the parameters of the model. Identifiability of the parameters of a specified bioelectrochemical devices were explicitly calculated and used to develop the applied potential/current protocols required for reliable performance.

Identification of the parameters provided design clues for optimising and then manufacturing can be applied to academic studies of redox chemistry. We anticipate the techniques will also offer new tools for the study of complex devices such as batteries, fuel cells and solar cells with opportunities to improve mechanistic understanding and operating efficiencies. We test our electrical performance and efficiency using advanced electrochemical approaches such as Fourier Transform Voltammetry, where the harmonics of the electrochemical response can real subtle details about reactor performance limitations and efficiencies.

BEV CORNABY

"TOWARDS SUSTAINABLE PACKAGING MATERIALS"

To support and amplify the impact of work CISL was undertaking on the relative impact of materials, in early February 2020, CISL organised and hosted CirPlas Forum 2: Relative impact of materials: connecting business, policy and research to deliver solutions. CISL designed the Forum event to (1) explore and showcase work being done in the University on the impact of plastics and the potential alternative materials and solutions, and (2) connect businesses, policy makers and scientists to discuss the challenge and share their perspectives, proposed approaches, and potential solutions. For CISL, the forum presented the opportunity to share and discuss the outcomes and implications of a scoping study it was undertaking on the relative impact of materials, getting feedback from the wide range of participants that attended. The feedback from the workshop informed the final report, Towards sustainable packaging materials: Examining the relative impact of materials in the natural source water and soft drinks value chain. The report contains a next step to "share the outcomes of this work with academics at the University of Cambridge and relevant experts to potentially inform research and the development of a methodology to model the future impact of materials that could guide decision-making", and we are now exploring how to take this forward to inform further research within the University. Through being part of the CirPlas network and hosting the forum, CISL has been able to engage a wide audience, including academics directly in business focused research, and has identified new opportunities to connect businesses and academics on potential new areas of research.

https://www.cisl.cam.ac.uk/resources/circular-economy/towards-sustainable-packaging-relative-impact-of-materials

PURSUING THE RIGHT OPTIONS

Plastic's properties of strength, manufacturability, low costs, and colour options make it prized among materials. The class of material we call plastics, is, however, far from a single homogenous material. Instead it is wide-ranging set of many materials and numerous products, each with its own unique set of characteristics. This is what makes plastics so practical and pervasive in modern society. But we need to stop thinking of plastics as one material and stop looking for a single solution to address plastic pollution problems.

This report presents a comprehensive view of UK plastics, including a novel analysis of material flows, stocks, and trade flows, along the supply chain (Fig.4). We've traced the post-consumer waste through to incineration, landfill and recycling, both in the UK and overseas (Fig.7). And we've calculated the current in-use stocks of plastic products for the UK (Fig.9) and used this to infer future demand for plastic (Fig.10) and generation of plastic waste (Fig.11).

We've noted that for some plastics flows, data are already prevalent, for example, the recycling rates of plastic packing, yet in other areas of the flow map, such as durable products, there are significant knowledge gaps and much research is still to be undertaken.

Two main environmental problems require urgent attention: the first is CO_2 emissions, where the UK's consumption of plastics generates 26 MtCO_{2e} emission across the whole life cycle; the second is pollution of waterways and oceans with plastic, which is much more challenging to quantify.

With the myriad of different plastic materials and products in use, it is little wonder that finding the right solutions to address emissions and ocean waste, for each material and product combination, is challenging. Each plastic has its own set of unique solutions and challenges.

For some plastics, such as PET, the separation, collection and recycling of the material is relatively simple; recycling rates for PET bottle approach 60%. Other plastics such as styrene-based polymers, are collected but not recycled in the UK. Recycling is particularly challenging for laminated materials in which different plastics are sandwiched together, e.g. nonwovens, blown films, blown bottles and extruded pipes. These waste plastics are sent overseas for 'recycling', with no guarantee that the materials will actually be recycled. For other plastics, such as PP and PVC the recycling process can use almost as much energy as making the plastic from virgin material. For these materials, recycling is rarely profitable, unless subsidies are applied or externalities costed.

When recycling is uneconomic incineration is an option: the energy from combustion is recovered as steam and used to generate electricity, thereby recouping some of the plastic's value. However, incineration produces CO_2 emissions, confounding the UK's target of net-zero emissions by 2050.

Landfill, the option of last resort, surprisingly accounts for one third of plastic waste treated in the UK. This solution, if facilities are managed well, avoids both CO_2 emissions and ocean waste.

For nearly 50 years we have promoted the waste hierarchy, where preferred options for waste treatment are (in order): waste prevention, reuse, recycling, recovery (incineration) and disposal (landfill). This approach has been successful in reducing waste to landfill (the least preferred option), with a five-fold reduction in standard waste going to landfill, between 1996 and 2015. Alongside this, we have actively promoted recycling, changing the whole culture of the nation to separate, clean and recycle their plastics.

Despite many years of waste hierarchy advocacy, plastic recycling in the UK has largely failed. Only 12% (0.4 Mt) of the plastic waste generated in the UK, is recycled in the UK. A further 0.7Mt is sent overseas for 'recycling' (we hope), and the remainder is either landfilled or incinerated. Furthermore, landfill of plastics is promoted by some as a potential method for carbon sequestration.

It is not surprising that pursuing a single solution, for a mixed bagged of plastic materials and products, has not yielded the dividends we had hoped. The waste hierarchy, it turns out, provides only a simple heuristic, which is inflexible for the myriad of plastics and products we produce. The one size fits all approach has failed.

In response, we propose a new hierarchy (see Fig. 13 below) to challenge and promote debate:

RETHINK, to push us to question if materials are really needed.

REDUCE the amount of material through lightweight design.

EXTEND LIFETIME by designing products that last longer or can be reused at end-of-life.

RECYCLING, RECOVERY, LANDFILL, are positioned at the same level of the hierarchy, with recycling no longer prioritised over energy recovery, and over landfill. Each of these options works for a select range of plastic materials and products. And in practice we currently recycle, incinerate and landfill in roughly equal proportions. Thus, we think it is right for a considered decision to be made between these six options, for every plastic we handle.

One final thought is to ponder whether we could go back to a time where we had less demand for plastics and fewer different plastic materials. This runs counter to our sense of inventiveness and progress. But what if, when we were inventing new polymers, we were to screen them, not just for functional performance and scale-up cost, but also against environmental impact and end-of-life options. Could we design our way out of the problems of CO_2 emissions and ocean wastes? Could designers, not just create new and more interesting polymers, but create new, more interesting, and more sustainable plastics?

Now there's a challenge!"

WASTE / EMISSION HIERACHY

PRODUCT SPECIFIC

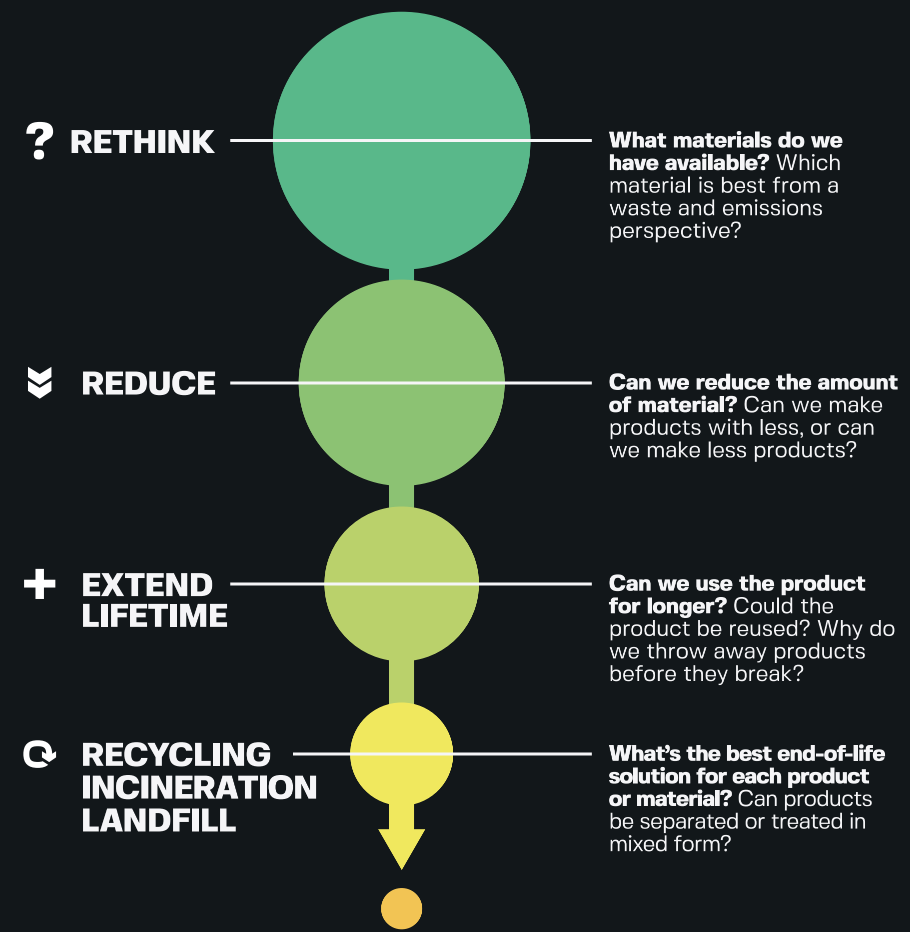


Fig.13 Waste/Emissions Hierarchy

We need tailored solutions for the myriad of plastics we use.

PROJECTS AND PARTNERSHIPS

CIRPLAS: THE CAMBRIDGE CENTRE FOR CIRCULAR ECONOMY APPROACHES TO PLASTIC WASTE

CirPlas

Urgent action is required for waste plastics as eight million tons of plastic enter the oceans every year and plastic pollution has become a serious threat to our local and global ecosystem. The export of British waste has reached record numbers in recent years as Britain does not have the requisite infrastructure to recycle its own plastic waste and severe shortages in landfills have become commonplace following China's restrictions in 2018 on foreign waste imports.

CIRPLAS is a recognised think-tank, nurturing a multidisciplinary research culture between global network of partners and a range of Cambridge-based research projects to tackle contemporary challenges from manufacturing more sustainable materials to driving innovations in plastic recycling. The 18-months UKRI funded project targets the development of a sustainable plastics economy by understanding the local and global distributions of plastics, innovating alternatives to plastics and developing novel technologies for the utilisation of waste plastics.

Find out more at **www.energy.cam.ac.uk/Plastic_Waste/about_cirplas**

C-THRU: CARBON CLARITY IN THE GLOBAL PETROCHEMICAL SUPPLY CHAIN

C-THRU

CARBON CLARITY IN THE GLOBAL PETROCHEMICAL SUPPLY CHAIN

It is hard to imagine the world without the modern petrochemical sector: chemicals and their derivatives are all-pervasive. Plastic, rubber and synthetic textiles adorn our buildings, vehicles and countless other elements of the modern built environment. Modern agricultural systems could not function without synthetic fertilizers and the pharmaceutical sector as we know it would not exist. Nevertheless, the modern petrochemical sector exerts a large environmental burden, being responsible for 30% of final industrial energy use, including 10% of global oil and gas demand, and drives 17% of global industrial CO_2 emissions. And demand for chemicals is expected to at least double by 2050.

C·THRU is 3-year international multi-disciplinary research project, which is funded by the VKRF Foundation and begins 1 October 2020. It aims to deliver foresight on the future interventions and innovation opportunities in the petrochemical sector required to minimise greenhouse gas (GHG) emissions. This will be achieved by delivering the world's most comprehensive, reliable and transparent account of current and future emissions for the sector. This account and the underlying modelling methods, tools and data will support strategic policy and business decision-making to promote the global sustainability of the petrochemical sector.

UK FIRES: LOCATING RESOURCE EFFICIENCY AT THE HEART OF FUTURE INDUSTRIAL STRATEGY

UK FIRES

Locating Resource Efficiency at the heart of Future Industrial Strategy

Legally binding targets to achieve net-zero emissions by mid-century have now been passed in eight countries including the UK, France, Germany and China. These targets are an extraordinary challenge for the complex supply chains that transform material resources into societal benefit. However, the requirement for radical change creates opportunities for innovation and could lead to a renaissance for manufacturing in the UK. Delivering net-zero depends on locating Resource Efficiency at the heart of future Industrial Strategy. This requires access to data on material use, information about options for change and evidence about successful pathways to deployment.

UK FIRES is a major research programme, comprising a consortium of subscribing industrial partners from resource-intensive sectors working with academics from Cambridge, Imperial College, Oxford, Bath, Nottingham and Strathclyde who are funded from 2019-2024 by a £5m programme grant from the EPSRC. The collaboration is co-ordinated through a Living Lab.

Find out more at **www.ukfires.org**

TECHNICAL NOTES AND REFERENCES

UNITS

kt - kilotonnes (thousand tonnes)

Mt - megatonnes (million tonnes)

CO_{2e} - carbon dioxide equivalent

SECTIONS

Page.4–PLASTICS ARE PRACTICAL: Global plastic production 2017, 438 Mt [1]; Global life-cycle GHG emissions of conventional plastic 2015, 1.7GtCO_{2e} [2]; Share of plastic by use [1]

FIGURES

Fig. 1 [1]

Fig. 2 Cement [3], Steel [3, 4], Aluminium [3], Glass [5], Plastic [6] (1950-2018)

Fig. 3 [1]; Fig. 8 [7]

Figs. 4-7 and 9-13 use our own modelling.
Fig. 7 UK post-consumer waste in 2016 is 3.8Mt (PlasticsEurope 2016 [30]). For 2017, 3.3Mt was calculated using PlasticsEurope data for recycling (2017) and the same shares for incineration/landfill/recycling; plastic waste 2017 export [21], marine debris and dump plastic waste [7]

TABLES

1-Plastic recyclability in the UK: Polymer recyclability [8-10] [11-14]; Ease of recycling [8, 9, 11, 15, 16]

BOX STORIES

1–WHAT GOES IN MUST COME OUT: Global plastic production, recycling content, global material stock, plastic end-of-life (1950-2017) [1], global plastic waste in 2017 [1]

2–GRASPING AT STRAWS: Plastic packaging recycling rates [17] [18], Consumption of plastic straws, plastic stirrers plastic-stemmed cotton buds [19], global plastic marine litter [6], share of plastic on UK beaches [20] [19], EU and UK Legislation [31], [32]

TAKE–AWAY TRAYS: The UK PS / EPS (polystyrene / expanded polystyrene) packaging consumption and share in consumer sector by type [21], PS / EPS plastic packaging waste recycling in the UK [22], PS / EPS kerbside collection rate in the UK [23]

3–OCEAN WASTE POLLUTION: Global plastic ocean waste [6], microplastic and microplastic definition [24], global microplastics waste in the marine environment [25], plastic waste mismanagement issue [26]

4–PLASTIC PACKAGING FILM: Plastic packaging film placed on the market in 2017 – 395 kt, 26kt of which plastic bags [27]. 18kt - kerbside collection, 16kt - export for recycling [21]

5–PLASTIC FOOD PACKAGING:

Food statistics / waste food statistics in the UK [28], top 20 vegetables and fruits waste in the UK from households, freshness test [29]. Calculations based on top 20 vegetables and fruits waste [29] including assumptions for editable parts, share of the packed in plastic film food, the plastic packaging weight, the number of packs. For the rest food waste from the UK household [28] as well as hospitality & food service and retail the same methodology was used.

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UK Research and Innovation

UNIVERSITY OF CAMBRIDGE

resource efficiency collective

Dr Jonathan M. Cullen
jmc99@cam.ac.uk

Department of Engineering
University of Cambridge
Trumpington Street, CB2 1PZ

Dr Michal P. Drewniok
mpd43@cam.ac.uk

Dr André Cabrera Serrenho
ag806@cam.ac.uk

Resource Efficiency Collective is a research initiative at Cambridge University. Together, we seek answers to a challenging question: how can we deliver future energy and material services, while at the same time reducing resource use and environmental impact? At the heart of the Resource Efficiency Collective lies a stock - standard research group, with the normal mix of PhD students, research associates and staff. But by calling ourselves a Collective we hope to be more inclusive, to blur the boundaries a little, and to invite our many friends and colleagues to participate. Please feel free to join in!

For more information please visit **www.refficiency.org**