21 Plastic

Plastic waste is in the public eye, but we already know from the labels on packaging that plastic recycling is complicated. Is plastics production as efficient as the production of other materials, and what can we do to use less, recycle more, or use plastics for longer?

We started the last chapter on a grand scale, with ancient Egyptian construction, so we'll start this one more humbly. In a teacup in fact, and without a storm either, just the gentle swirling of the tea being stirred. Our humbler start reflects the fact that the family of plastics is quite different from our other four materials, with so much variety that it is much more difficult for us to make estimates of future emissions associated with their production because each sub-class of plastic deserves at least a chapter of its own. But the family of plastics sits there on our opening pie chart as one of our five materials of concern, so strengthened by our cup of tea we need to set off, and we'll start not with a toe in the water, but a spoon in the tea.

Stainless steel teaspoon

Most of the world's teaspoons are made from stainless steel or plastic. Stainless steel is 20 times stronger than polystyrene (a plastic typically used for making plastic cutlery) 65 times stiffer, and about 8 times more dense. So, for equivalent strength, we'd expect the plastic teaspoon to be around three times heavier than the stainless steel one and be 20 times larger. But compare the two teaspoons in the photos, and the opposite is true: the plastic teaspoon is lighter and has less volume. Obviously this is mainly because the two spoons are designed for different needs: permanent 'quality' and disposable 'trash'. But take a close look at the second photo, at the back of the plastic teaspoon. The stainless steel teaspoon was cut out of a uniform thickness sheet and then formed to shape, but we can see that the plastic teaspoon has a much more complex geometry. In fact this shape is familiar from chapter 12, because it has been partially optimised. So a crucial difference between producing cutlery from plastic rather than metal is that plastic spoons are injection moulded, squeezed under pressure into a precise mould, allowing very precise control of complex geometry, while the metal spoon was stamped out of a sheet.

Plastic teaspoon

Next, take a look at our two family portraits—a diverse family of stainless steel teaspoons, and a diverse family of plastic ones. At the end of their lives, we can recycle all the metal teaspoons and make new ones without difficulty. But at the end of life of the plastic ones, although they could each individually be recycled, they cannot be recycled together—because the colours (and possibly other 'filler' materials) in the different spoons are all different. In addition, if we had thrown them all into our normal waste bin, they would reach the waste management company mixed in with all other waste. While we have some good technologies to separate out the metals (we have to work harder with stainless steel because it is only weakly magnetic, but it's still possible), but it is much more difficult to separate the plastics in a cost effective manner. Finally, the stainless steel teaspoon is worth more money, so we're much more likely to look after it than the plastic teaspoon which is worth very little. Unfortunately this is also true for many uses of plastic, and small pieces of used plastic have very little monetary value.

Colourful families of teaspoons

We've now set up a rather difficult agenda for our survey of plastics: there are many different types of plastic, most of which can be recycled, but only if perfectly separated from other types; manufacturing with plastic allows us to make very intricate efficient shapes, so in contrast to what we saw with metals, we may not be able to redesign goods to use much less plastic; plastic tends to be discarded in small pieces in mixed waste streams, from which it cannot easily be separated, so post-consumer recycling rates are currently low.

To understand our options for creating a sustainable material future for plastics, we need to look carefully at the different types of plastic, survey current and future uses, explore the efficiency of existing production, and see if we have any options for future material efficiency.

Plastic materials and their production

'Plastics' describes a broad category of materials, the name derives from the Greek *plastikós* meaning 'able to be moulded'. There are two distinct families of plastics—thermoplastics, which can be melted and reformed several times, and thermosets, which cure irreversibly on being heated, mixed or irradiated, so cannot be recycled. Thermosets include the materials used to make electrical fittings, and those that bind composite materials such as glass or carbon fibre composites used to make boats. They are the smaller branch of the family, so we will limit our interest to the larger branch of thermoplastics.

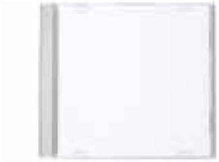
The first thermoplastics were made from natural materials. In 1823, Charles Macintosh of Glasgow experimenting with naphtha, a by-product of natural tar (a resin produced from pine trees) found that it allowed him to join layers of rubber, and so create a waterproof coat—to which he gave his name. In 1845, Thomas Bewley, a Dubliner, set up the Gutta Percha company in London, following a suggestion from Macintosh's brother and a request from the electrical pioneer Michael Faraday, to exploit the properties of the natural latex derived from the sap of the South East Asian Gutta Percha tree. Having invented an extrusion machine to produce insulated electrical cables, they went on to use Gutta Percha to transform the golf ball and initiate root canal fillings in teeth. In 1856, Alexander Parkes from Birmingham patented his invention of 'Parkesine'—the first manufactured thermoplastic, derived from plant cellulose, which itself was a commercial failure, but later developed into celluloid and was the basis of Kodak's films. In 1907, Leo Hendrik Baekeland, made the first (thermosetting) plastic from phenol, a synthetic (i.e. non-natural) polymer, derived from coal tar, and called it Bakelite.

But plastics innovation and production really gathered pace after the first world war, once oil extraction was widely established, and the distillation of oil allowed production of ethylene. After the second world war, production of plastics expanded rapidly, and many new plastics such as polystyrene and polymethylmethacrylate (commonly, and for obvious reasons, known as PMMA) were developed. As the production processes improved, so did the properties of the plastic products they made, and because of their low cost, plastics were used widely. Since then, many new plastics have been developed for use in demanding applications such as healthcare.

Most plastics today are made from oil, but there are many different production routes, which create diverse plastics with their own chemical and physical structure. The main plastics in common use are:

- **PE (Polyethylene, high and low density):** this is the most common and versatile plastic. Its properties can be tailored to many different applications, the most common of which are packaging (e.g. plastic bags and films), bottles and children's toys. It is used in both low-density (LDPE—low density polyethylene) and high-density (HDPE—high density polyethylene) forms, as appropriate to the application. LDPE is used primarily in packaging and film, while HDPE is used for stronger, stiffer products, such as pipework.

- **PP (Polypropylene):** this plastic is tough and flexible, widely used in textiles, stationery, automotive components and also in packaging.



- **PS (Polystyrene):** the properties of polystyrene can be tailored to a number of a different uses. Expanded polystyrene is used as protective packaging, and is extremely light. However, polystyrene can also be moulded into teaspoons, plastic cups and CD cases, for example.

- **PVC (Polyvinylchloride):** PVC is both cheap and versatile. It is used in a wide variety of applications, from pipes and fittings to canoes and garden hoses.

- **ABS (Acrylonitrile butadiene styrene):** this plastic is very tough and easy to mould. It is commonly used for safety helmets, casings for machinery (e.g. power tools), and in children's toys, such as Lego™.

- **PMMA (Polymethylmethacrylate):** PMMA is particularly useful as a tough, transparent plastic. Its first major application was in the canopies of fighter aircraft in the Second World War. Today it is often found in safety spectacles and windows.

- **PA (Polyamide):** the most common use of this plastic is as Nylon, used in a wide variety of clothing. But this tough material is also used in car tires, nylon-fibre ropes, light duty gears and tubing.

- **PET (Polyethylene terephthalate):** this plastic can be processed for very demanding applications. In one of its most common uses as beverage can bottles, it must be strong enough to contain the pressurized liquid.

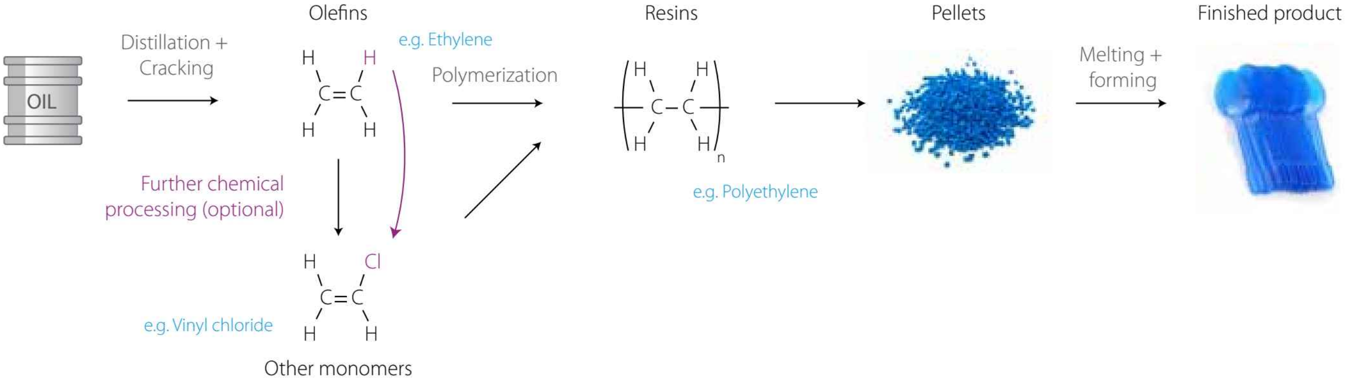
- **PUR (Polyurethane):** one of the most eye-catching uses of this stretchy material is in Lycra or Spandex. But it is also used in a stronger, stiffer form for gears, bearings and wheels.

The properties of each plastic arise from the chemistry of the different monomers used in their production, but some properties such as strength and stiffness can be influenced through the use of additives, fillers, heat treatment processes and mechanical deformation. Therefore a wide variety of different properties can be produced from a single type of thermoplastic. However, certain general properties explain the choice of particular plastics for certain applications. For example the presence of styrene in the monomer structure in ABS gives a glossy, shiny finish, which is popular for childrens' toys. PVC, PE, PP and PS all exhibit excellent chemical resistance, so PE and PP are used in packaging, and PVC in pipes where chemical corrosion may be a problem. Other key properties which are determined by the chemistry of the plastic include electrical and thermal resistance, resistance to weathering and resistance to humidity[1].

Thermoplastic production, summarised in Figure 21.1, begins with ordinary crude oil. The oil is first distilled to separate out its different components, some of which are treated in a process known as 'steam cracking'. In steam cracking, the oil distillate is mixed with steam and then heated in the absence of oxygen, to create smaller light molecules in the family of olefins, including ethylene and propylene. Olefins are a type of monomer, the fundamental building block from which plastics are made. We can use olefins directly, or we can use further processing to produce a wider range of monomers, such as vinyl chloride, where one of the hydrogen atoms in the ethylene molecule is replaced with a chlorine atom. These monomers are then polymerized, a process in which many copies of a monomer are joined into long chains, polymers, from which plastics are made.

The polymer chains are manufactured into 'resins', similar to the resin of a plant, which are the basic commodity of the plastics industry. These resins are subsequently processed into cylindrical pellets, which are supplied to product manufacturing companies. The pellets are melted and fed into a forming process,

Figure 21.1—**Process chain for thermoplastic production**



such as extrusion, to produce a finished product. Because the properties of the polymers are mainly determined by their chemistry, this last stage of production is entirely about geometry: so unlike metals, plastics can be formed directly and efficiently into finished shapes, with no need for any further processing. Unlike metals, the energy required to make plastics varies very little between different types, and is around 80 MJ/kg, and as plastics are usually made from oil, their emissions are also very similar at 2-3 kg CO_2/kg.

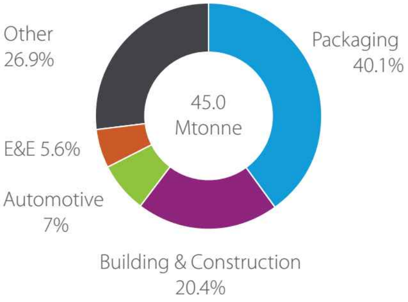


Figure 21.2—**Plastic product categories in Europe**

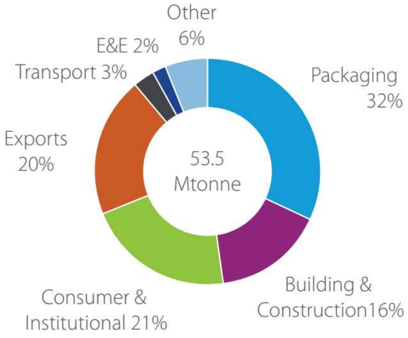


Figure 21.3—**Plastic product categories in the US**

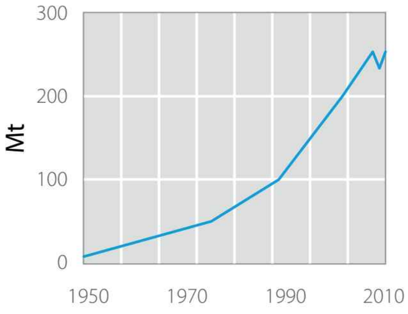


Figure 21.4—**Global growth in plastics demand since 1950**

Our uses of plastic

Globally, current production of plastics is around 230 Mt per year, or around 33 kg per person per year averaged over the world. Of course the consumption of plastic isn't averaged uniformly, and in Europe, Japan or the US our consumption is around 120 kg per person year. We saw in chapter 2 that a family of five in the UK uses around 1 kg of plastic packaging per week to bring their food home from the supermarket, equivalent to 11 kg per person per year (of which around 1 kg was in the carrier bags.) So where's the rest of it?

The two pie charts of Figures 21.2 and 21.3 show the main uses of plastics in Europe and the US, dominated by packaging and uses in building and construction. The figure implies use of around 50 kg of plastic packaging per person per year, five times what we brought home from the supermarket, for other shopping, and all the packaging we didn't see as our goods were shipped into and around the UK prior to arriving in shops. 25 kg of plastics per person are used in building and construction to provide water supply and drainage, lighting, lightweight roofs, cladding and frames for windows, doors and decorative features, electrical trunking and cables, insulation, seals and gaskets.

And all this demand has essentially grown since the Second World War, and continues to grow rapidly. Figure 21.4 shows the history of global production of plastics from 1950 to the present, doubling every 15 years. The International Energy Agency forecasts that by 2050 global demand will be 470 Mt, one further doubling, which if anything seems conservative. Figure 21.5 shows growing demand per person in key regions, with no evidence of a plateau in developed economies, and strong growth, more than 6% per year, in Asia and Eastern Europe. If demand for plastics will double or more in the next 40 years, can we produce plastics four times more efficiently to halve total emissions?

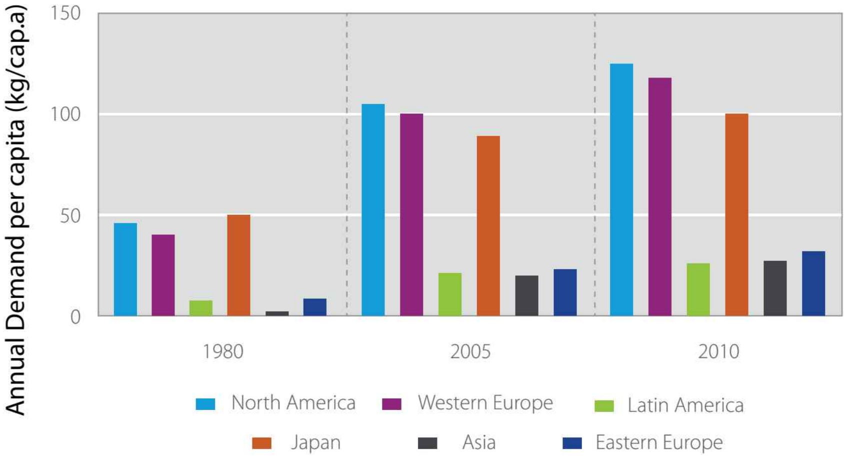


Figure 21.5—**Regional growth in demand for plastics since 1980**

Plastics with one eye open: can we make or recycle plastics more efficiently?

The International Energy Agency[2], in reporting on future energy efficiency options in the plastics industry, estimates that using more efficient steam cracking with higher temperature furnaces, gas turbine integration, advanced distillation columns and combined refrigeration plants could lead to a 15% saving in energy required per unit output of typical plastics. Further efficiency gains will be possible in downstream manufacturing operations as we saw in metals production, but these processes use much less energy than is required to convert oil to basic plastic pellets.

Just as we found in the steel and aluminium industries, there are few remaining opportunities for energy efficiency in plastics production. However, like metals and unlike cement, there is a recycling route for plastics: can we increase the rate of collecting plastics and can we then recycle them more efficiently?

Our opening story with teaspoons demonstrated the difficulty of plastics recycling is, in which different plastic types cannot be mixed. But in fact the story is even worse, because the great variety of additives (to change colours or properties) and fillers (cheaper materials such as chalk which increase strength and hardness) used in commercial plastics tend to degrade the properties of recycled mixed plastic. For a company manufacturing plastic products it is relatively straightforward to recycle plastic scrap generated during production, because the quality of the recycled material is known and it can be separated from other types of plastic. But once plastics have entered general waste streams, it is extremely difficult to separate them with sufficient precision.

Plastic scrap from manufacturing processes is already recycled at a very high rate, as it is automatically segregated without contamination, and can often be recycled back into the same machine that created the scrap. It is unlikely that rates of recycling in this part of the scrap stream can be increased. Therefore increased recycling of plastics depends on two developments: improved separation of plastics from other municipal waste, and improved sorting. Increasing recovery rates is difficult, as plastic waste is often fragmented and diverse. Sorting plastics is also challenging, particularly because many plastics have similar densities and optical characteristics.

Could we improve the recycling technologies themselves? There are four distinct classes of plastic recycling. Primary recycling in which material is directly re-extruded, is simplest, but only possible with a pure waste stream, and therefore only really suitable for recycling process scrap. In secondary (or mechanical) recycling, plastics are ground into small chips or powder, which is then washed, dried and

Plastic Recycling Labels

Plastic products carry labels to identify the type of plastic from which they are made, and indicate whether or not the product can be recycled.

These plastics are widely recycled throughout the EU and the US

These plastic types are hard to recycle, so are sent to landfill or incinerated converted to resin for re-use at the beginning of the process. This route does not require such a pure scrap source, but contaminants will reduce the quality of the recycled material. In tertiary recycling the old plastic is broken down chemically to produce new feedstock which can be used either to make new plastics, or in other applications. This may occur, for example, in a process called pyrolysis in which unsorted plastic waste is heated in a furnace from which most oxygen has been excluded, to prevent combustion. Plastics recycling by pyrolysis is technically feasible, and has been demonstrated in pilot scale facilities, but to date the energy and financial cost of production has been prohibitively high.

Finally quaternary recycling (energy recovery) aims not to recycle the plastic for use, but to recover the energy embedded in it, through incineration. Burning plastic releases energy, and provided the incineration process is run efficiently so that harmful volatile organic compounds are not released, it is a better option than dumping the plastic waste in landfill. The calorific value (stored energy) of plastic is similar to that of fuel oil, so it can provide a valuable source of energy if burnt in appropriate conditions.

A biodegradable bioplastic bag

Sugar cane—a key feedstock for bioplastics production

Are there any novel technologies that might transform the production of plastics? In the route from oil to plastic, this is unlikely but the area which attracts more attention is the production of plastics from plants, by exact analogy with the production of 'bio-fuel' for energy that we briefly discussed in chapter 9. As we saw earlier in this chapter, the production process for plastic begins with the production of olefins from crude oil. But in fact, one of the most common olefins, ethylene, can be produced from plants such as sugar cane. This bio-ethylene can be used to produce polyethylene which is identical to that produced from crude oil. Bioplastics can also be produced from other plants, and unlike plastics made from crude-oil, can biodegrade. As well as conserving oil supplies, production of bioplastics uses less energy then plastics derived from crude oil. However, just as we saw in considering biofuel earlier, production of plants to make bioplastics requires land, which therefore cannot simultaneously be used to grow food.

So, with one eye open, we've identified a potential 15% cut in energy required per tonne of plastic produced, and two other major possibilities: converting waste plastic back to oil and supplying bio-plastics instead of oil-plastic. The first of these is not yet operating at scale, and the second will be constrained by pressure on land-use. It is therefore very unlikely that we can reach our target 50% absolute cut in emissions for plastics with one eye open. In fact, the most aggressive (i.e. least emitting) forecast constructed by the International Energy Agency assumes emissions from plastics production will more than double from 2005 to 2050, unless CCS is applied both to electricity generation and all other fuel combustion associated with plastic production. We clearly need to look also for options with both eyes open.

Plastics with both eyes open: can we deliver plastic services with less new material?

In our opening foray into the world of teaspoons, we saw that plastic products can already be optimised, because they can fill complex moulds effectively, as part of normal injection moulding processes. Production of plastic parts leads to few yield losses: for example injection moulding is a net shape process, with losses only on the 'runners' through which plastic enters the mould, and with more advanced processing (runnerless moulding), can have no losses at all. So the first two of our strategies from looking at metal with both eyes open offer little benefit, and as the process generates little scrap, there is not much of that to divert, which rules out the approach of chapter 14 also. Our hope for reducing demand for new plastic then relies on keeping products for longer, re-using them at end of life, or of course, on reducing overall demand.

If we concentrate on packaging, we've established that in the UK we probably take around 10–20 kg of plastic packaging per person into our houses each year, yet we cause 50 kg of plastic packaging to be made. So approximately 30 kg of plastic packaging per person is required to move goods from factory to factory or shop. This industrial packaging is hidden from our consumer eyes, so unlike consumer packaging, exists solely to protect goods in transit. This industrial packaging is an excellent target for life extension through re-use. Although it has a relatively low monetary value, industrial packaging accounts for around a quarter of all plastic consumption in the UK, so re-use could have a significant impact.

Used PET bottles

In construction, plastic pipes rarely fail, so ensuring long life and re-use should be feasible—although again, with a low economic value, there is little incentive to dismantle and re-sell old pipe. The difficulty in looking for opportunities to reuse or extend the life of plastic products is that it is cheap and versatile, so used in a plethora of low-value applications. However, a large fraction of plastic use is to make components for use in complex products such as cars. Extending the life of these products, which will also reduce demand for other materials, will help to reduce demand for new plastic production.

If we can't find enough opportunities for re-use and life extension, we must then examine demand reduction. For example, we know we could live with less disposable packaging, because it is a relatively recent invention. This is not a strategy that will be pursued by the plastics industry, but in the absence of other options for emissions saving, demand reduction may be the key policy requirement for cutting emissions in plastics production. At the start of chapter 2, when we looked at domestic plastic waste, we saw that we each use about 1 kg of plastic supermarket bags per year, but more like 7 kg of plastic bottles. So the next time the Prime Minister wants to identify opportunities for saving plastic, we suggest the focus should be on bottles and not bags.

Outlook

Plastics are the most complicated material family of the five we are considering in this book. In our survey of options for change, we have not found enough options to make a 50% cut in emissions while demand doubles. We have four positive suggestions out of the chapter:

- To reduce the variety of plastics in use to simplify recycling and increase recovery rates.

- In recognising the energy benefit of combusting plastic for energy, to work intensively on generating fuel oil from used plastic.

- To replace all possible disposable packaging with long life packaging in continuous re-use and to extend the life of all non-disposable plastic goods.

- To promote life extension for other products, including vehicles, which contain many plastic components, as a part of a general strategy for reducing demand for new materials.

This has been a tough journey, although we've found a few good opportunities to explore, so it's time for another cup of tea.

Notes

Plastic materials and their production

1. Further information on the properties of plastic can be found in Callister (2003).

Plastics with one eye open: can we make or recycle plastics more efficiently?

2. The details of the IEA scenario analysis can be found in their Energy Technology Perspectives report, IEA (2008a)