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Article - Special issue on Designing Law and Policy Towards Managing Plastics in a Circular Economy

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1 INTRODUCTION

It has long been recognised that plastic objects released into the environment have harmful impacts on wildlife. Public realisation that plastic pollution is a major global environmental problem is more recent and has been sudden, sparked by publication of an analysis of the flows of polluting plastics into the environment and the accumulated stocks of polluting waste, particularly in the oceans.[1] This contribution aims first to provide an introduction to the history and uses of plastics in the economy and, secondly, to set out the routes by which plastics leak from the economy into the environment in order to inform development of possible strategies to alleviate the problem of plastic pollution.

The word 'plastic' refers to a very broad range of materials with different chemical compositions, mixed with an even broader range of additives to provide specific functional properties. In strict scientific terms, a plastic is a material that deforms permanently when subjected to shear; plasticine and butter are examples of materials with plastic properties. However, in popular usage, *plastics* refers to a group of materials which may or may not have plastic properties: solid substances consisting of polymeric materials made up of macro-molecules containing carbon and hydrogen and sometimes other elements, notably oxygen, mixed with other materials such as plasticisers, fillers and pigments added to enhance properties such as processability, strength, texture and durability. Some of the additives are themselves the cause of environmental problems; for example, some commonly used plasticisers (i.e. chemicals added to impart specific properties, usually to make the 'plastic' material easier to form into a required shape) are recognised endocrine disruptors, implicated particularly in impacts on the health of fish and other aquatic organisms. However, the focus here is on solid objects formed from plastic. More specifically, we focus on *thermoplastics* (roughly, polymers that soften to show plastic or fluid behaviour when heated) rather than thermosetting polymers (which react to become permanently rigid when heated or mixed with a catalyst to promote a polymerisation reaction). Bakelite, polyurethanes and epoxy resins are examples of thermosetting polymers. Thermosetting polymers are generally durable and are therefore used primarily for products with long service lives. Thermoplastics are more commonly used for applications with short service lives and so dominate the flows of plastics through the economy. The focus here on pollution by plastics implies a focus on thermoplastics, which make up the great majority of the problematic plastic waste.[2]

Polythene (more correctly, polyethylene) is the most widely used thermoplastic, and was one of the first to be used in consumer goods. Polyethylene was first made, almost by accident, in March 1933 by researchers at Brunner Mond & Co., a company that subsequently became part of Imperial Chemical Industries (ICI).[3] At first, the commercial value of polyethylene was not recognised. It only went into production to meet the need for an effective electrical insulator in the radar equipment being developed as part of the preparations for the impending World War.[4] Thus, polyethylene was initially seen as a valuable specialised material with properties that made it ideal for specific demanding applications. The originators of polyethylene did not foresee that thermoplastics would come to be used universally (and would have been aghast to see how bulk plastics have been mis-managed).[5]

Widespread non-military use of polythene and other plastics developed after the Second World War, to the current point where they are so embedded in everyday life that there is not (and should not be) any question of eliminating plastics completely from the economy. Global production of plastics rose to more than 400 million tons in 2015.[6] Uses include some for which particular material properties are needed, for example

1 Jenna R Jambeck and others, 'Plastic Waste Inputs from Land into the Ocean' (2015) 347/6223 Science 768.

2 Roland Geyer, Jenna R Jambeck and Kara L Law, 'Production, Use and Fate of all Plastics Ever Made' (2017) 3/7 Science Advances e1700782.

3 William J Reader, *Imperial Chemical Industries; vol. 2 - The First Quarter Century: 1926-1952* (OUP 1975) 349-362.

4 E Raymond Ellis, Polythene Came from Cheshire (ER Ellis self-publication 2005) 11-16 and 25-29.

5 WR Dermot Manning, Personal Communications, 1978 to 1984. Note that Dermot Manning was part of the group that made the first polyethylene and the engineer who developed the first industrial process to produce the material. He was the father-in-law of one of the authors (RC) who recalls his lively anecdotes and regards them as primary source material.

6 Geyer, Jambeck and Law (n 2).

continuing the original use of polyethylene in electronic devices; uses with long lives, such as in construction and other durable products; convenience applications with short service lives, such as packaging; and some consumer uses, such as cosmetics, designed so that the plastic is released into the environment after use. Packaging is the dominant use, accounting for about 40 per cent of the plastics produced,[7] but is by no means the only use for which society depends on plastics. Right from the first use in electronic devices, most plastics have been designed and formulated to be stable and durable. Their persistence is one of the principal reasons why plastics have become a major environmental problem.

The approach to be explored here is not to try to eliminate plastics from the economy, but rather to reduce and eliminate 'leakage' of plastic from the economy into the environment. 'Leakage' and 'waste' are not the same: 'waste' materials (i.e. materials that have been used and discarded) can be re-used, recycled or handled by managed disposal, whereas 'leakage' refers to unmanaged release into the unconfined environment. Improving management of used plastics to avoid leakages requires insights that combine understanding of the material properties of plastics, their uses, how discarded plastics can be managed, and the technological options for re-use, recycling and management of waste. This paper is intended to support this understanding by mapping the main flows of plastics through the economy, identifying where and how leakage occurs, and there by provide a basis for targetting the most leakage-prone items. It differs from other papers,[8] by adopting a perspective rooted in Life Cycle Assessment (LCA) and Industrial Ecology, augmented by insights from waste management and social perspectives on the sources of plastic pollution.

LCA has developed since the 1980s as an approach to assessing the full environmental impacts of delivering a product or service, by mapping the flows and operations in the complete 'cradle to grave' product chain, quantifying the inputs and emissions, and assessing their environmental significance.[9] LCA has been systematised through a series of ISO standards.[10] The approach is used routinely by both private and public sector organisations to assess, manage and improve the environmental profile of economic activities. Life cycle thinking is increasingly used as a basis for regulation. Industrial Ecology extends life cycle thinking to 'study the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory and social factors on the flow, use and transformation of resources'.[11] Industrial ecology thinking underlies concepts like the 'circular economy'.

The focus here is on possible ways to alleviate the environmental problems caused by plastic pollution, not on the much less significant problem of using non-renewable resources to make plastics. Plastics are produced mainly from fossil hydrocarbons (i.e. oil and gas) but account for less than 4 per cent of the chemical output of the oil, gas and petroleum sector,[12] which is in any case much smaller than the sector's output of fuels. Given that known reserves of fossil hydrocarbons are many times larger than the maximum quantities that can be exploited without causing catastrophic climate change,[13] the availability of feedstock to make fossil-based plastics is not a long-term concern. Furthermore, production of 'natural' biotic materials (notably cotton,[14] which is sometimes advocated as an alternative to plastic for uses like shopping bags) frequently requires far more non-renewable resources in the form of fertilisers and other agrochemicals, irrigation water and land. Land and, in many parts of the world, fresh water are already scarce resources. Organic cultivation does not solve this problem: it may reduce fertiliser and agrochemical inputs but at the immediate expense of reduced yield, so that more land must be cultivated to maintain output.

7 ibid.

8 Kara L Law, 'Plastics in the Marine Environment' (2017) 9 Annual Review of Marine Science 205; CJ Rhodes, 'Plastic Pollution and Potential Solutions' (2018) 101(3) Science Progress 207.

9 Henrikke Baumann and Anne-Marie Tillman, *The Hitch Hiker's Guide to LCA* (Studentlitteratur, Lund 2004).

10 International Organisation for Standardisation (ISO), 'Environmental Management – Life Cycle Assessment – Requirements and Guidelines', ISO 14044: 2006.

11 Robert White, 'Preface' in Braden Allenby and Deanne Richards, *The Greening of Industrial Ecosystems* (National Academy Press 1994).

12 John Abbott, 'Reduction in Plastic Use Won't Hurt Petrochemicals Industry' *The Chemical Engineer* (July/August 2018) 4.

13 Jeremy Leggett, *The Energy of Nations: Risk Blindness and the Road to Renaissance* (Earthscan 2013).

14 Valentina Bisinella and others, Life Cycle Assessment of Grocery Carrier Bags (Danish Environmental Protection Agency, Miljøprojekter, No. 1985, 2018).

2 PLASTICS IN THE ECONOMY

2.1 Conventional Hydrocarbon-based Plastics

Figure 1 shows the industrial ecology of thermoplastics produced from fossil hydrocarbons, primarily from petroleum; i.e. it presents a generic map of the flows and uses of thermoplastics in the economy.[15] The figure embodies a 'closed loop' approach to the use of plastics; i.e. it shows a form of 'circular economy' (although this analysis of the use of plastics predates the upsurge of interest in a circular economy). The possible approaches to managing plastics in and following use, i.e. the activities available to promote a circular economy for plastics and reduce leakage, are summarised in Table 1. Current uses of plastics follow the routes mapped in Figure 1 but usually without all the possible re-use and recycling loops.

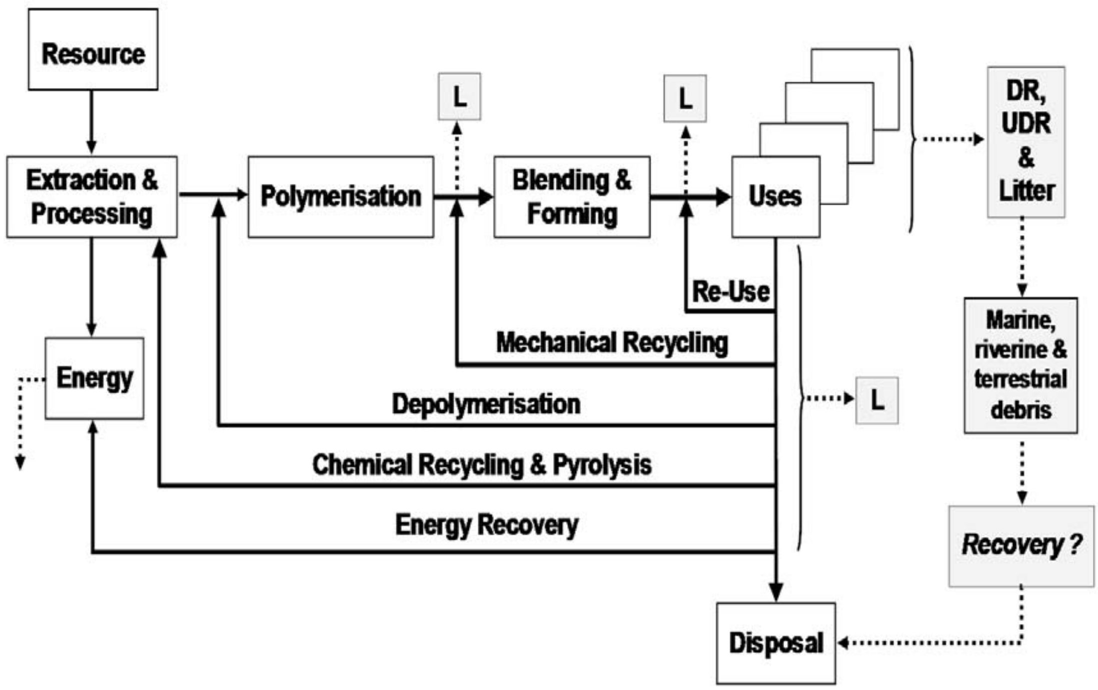

Figure 1. Industrial ecology of oil-based plastics (adapted from Clift)[16]

[DR = Designed releases; UDR = Undesigned releases;
L = Losses from transport and transport packaging]

15 Roland Clift, 'Clean Technology – The Idea and the Practice' (1997) 68 J Chem Tech Biotechnology 347.
16 ibid.

Table 1. Management options for plastics in the economy

Product or Material	Management options
Leakage-prone articles	Eliminate/redesign Reduce Replace
Specific articles	Re-use Remanufacture
Specific materials	Mechanical recycling Depolymerisation Chemical recycling
Mixed plastic waste	Chemical/feedstock recycling Energy recovery
Degraded mixed waste	Landfilling

Starting in the top left corner of Figure 1, oil that provides the feedstock for conventional plastics is extracted and transported to a refinery where it is processed into fuels like gasoline, diesel, kerosene and heating oil (see the 'Energy' box in Figure 1) and also a range of petrochemical products including the different monomers from which plastics are made; e.g. ethylene for polyethylene. Where natural gas is used as the feedstock, the same sequence of extraction and processing is followed. The monomers go through polymerisation reactions to produce raw polymers, commonly in the form of pellets. The pellets are blended with additives (see Introduction) and formed into material products.

Beverage bottles provide an informative and representative example of a specific plastic product. In general, the longer the functional life of the plastic product, the lower is the flow of plastic into the economy to provide the function.[17] Therefore, in principle, a plastic product or component should be re-used as many times as possible, but this requires a well-developed system for separate recovery or separation of used items. Deposit/return systems for beverage containers illustrate this approach to making items less leakage-prone. In principle, recovered containers can be re-used; for example, bottles can be refilled. However, this may be too costly; for example, refilling may require the container to be more robust than a single-use bottle and therefore formed from a larger quantity of plastic.

In any case, any material item will eventually become contaminated or damaged to the point where it cannot simply be re-used (Table 1). Objects that cannot be re-used can sometimes be recycled mechanically: i.e. the plastic is shredded or chipped so that it can be reformed into the same product or into a different product with lower specification so that some degree of contamination is tolerable. However, this recycling route is only open if mingling of different plastic materials is avoided.

For the greatest efficiency in the use of plastics, they should be used as many times as possible,[18] by keeping plastic items within the flows in the top right corner of Figure 1. However, components eventually become so contaminated or co-mingled with different plastics or other materials that they cannot simply be re-used or shredded and reformed. Furthermore, the additives used to make a particular plastic suitable for its first use limit its subsequent uses.[19] There is limited scope for forming mixed waste plastic (Table 1) into low-specification single-life products, such as garden furniture or fencing, but the quantities that can be used in this way are small and there is little prospect that they could grow to be a significant proportion of the total plastic waste. In any case, such secondary products have finite lives, so that they will inevitably end up as part of the mixed plastic waste stream in their turn. Therefore, to avoid complicating Figure 1, these uses are not shown.

More generally, from the point in the industrial ecology where plastic objects have become too contaminated or mixed for re-use or mechanical recycling to be viable, further recycling requires chemical reprocessing rather

17 Walter R Stahel and Roland Clift, 'Stocks and Flows in the Performance Economy' in Roland Clift and Angela Druckman (eds), *Taking Stock of Industrial Ecology* (Springer 2016) 137.

18 ibid.

19 John N Hahladakis and others, 'An Overview of Chemical Additives Present in Plastics: Migration, Release, Fate and Environmental Impact During their Use, Disposal and Recycling' (2018) 344 J Hazardous Materials 179.

than mechanical re-forming (Table 1). A few specific polymers can be depolymerised (a form of chemical recycling); i.e. converted back into monomers which can be returned as input to polymerisation. In principle, this may enable the plastic to be returned to a high-value use by removing biological contamination, but the concentration of additives and level of material contamination or mixing with other plastics must be small. At this point in the industrial ecology, the waste is usually a mixture of different plastics with variable composition and low material value. Processes are becoming available for chemical recycling of mixed plastics: the plastics are converted into a mixture of hydrocarbons that can in principle be returned to an oil refinery to be processed, along with fresh petroleum, into refinery products including the monomers for plastics,[20] or into a synthesis gas that can be used as feedstock to make other chemical products or as a fuel gas for power generation (see Figure1).[21] However, there are barriers even to this form of chemical recycling. Additives can complicate or prevent chemical recycling.[22] Furthermore, petroleum refineries are understandably reluctant to accept a small recycled input whose composition and properties may be variable and which could contain components that would disrupt refinery operations, for example by contaminating catalysts.

Most plastics have high fuel value. For plastics that have become so mixed or contaminated that material recycling would require major processing, energy recovery can be preferable on both environmental and economic grounds. Mixed plastic waste that is not recycled can be used as an energy source, usually mixed with other combustible components of solid waste in the form of Refuse-Derived Fuel (RDF). RDF is most commonly used for industrial or neighbourhood heating or for generation of electrical energy,[23] thereby offsetting some of the demand for fossil fuels.

Finally, to avoid leakage into the environment, waste plastic not recycled or used as a fuel must be disposed of in managed landfill. The durability of most conventional plastics ensures that they remain in the landfill permanently but some additives, notably plasticisers, may leach out and potentially contaminate groundwater.

2.2 Alternatives to Conventional Plastics

As alternatives to the conventional fossil-based plastics whose industrial ecology is described above, two 'new' classes of plastics have been developed over the last 20 years or so: biodegradable and bio-based plastics. These classes are distinct but overlap.[24] 'Biodegradability' refers to the propensity of a plastic to break down under the influence of micro-organisms in landfills, composting and anaerobic digestion waste management systems or in the wider environment. However, only a few types of 'biodegradable' plastic actually degrade within a few weeks in the natural environment (see below). Bio-based plastics differ from Figure 1, being derived from biological materials rather than fossil hydrocarbons, but this difference is restricted to the top left corner of the Figure, up to 'Blending and forming': from there on, uses of a bio-based plastic follow the industrial ecology of a conventional plastic. Bio-based plastics are much less significant in the economy than conventional plastics, representing about 1 per cent of total plastics production.[25] The biodegradability of a plastic depends on its composition, not on how it is made: some bio-based plastics are non-biodegradable, just as some made from fossil hydrocarbons are biodegradable.

20 Mathew Gear and others, 'A Life Cycle Assessment Data Analysis Toolkit for the Design of Novel Processes – A Case Study for a Thermal Cracking Process for Mixed Plastic Waste' (2018) 180 J Cleaner Production 735.

21 Sara Evangelisti and others, 'Integrated Gasification and Plasma Cleaning for Waste Treatment: A Life Cycle Perspective' (2015) 43 Waste Management 485.

22 Hahladakis and others (n 19).

23 Umberto Arena and Fabrizio DiGregorio, 'A Waste Management Planning Based on Substance Flow Analysis' (2014) 85 Resources, Conservation & Recycling 54.

24 Martin K Patel and others, 'Second-Generation Bio-Based Plastics are Becoming a Reality - Non-Renewable Energy and Greenhouse Gas (GHG) Balance of Succinic Acid-Based Plastic End Products Made from Lignocellulosic Biomass' (2018) 12 Biofuels, Bioproducts & Biorefining 426.

25 European Bioplastics <https://www.european-bioplastics.org/market>.

Biodegradable plastics have the property that they can break down, under the influence of natural micro-organisms or other biota, into simple molecules which disperse in the environment, ideally without causing environmental damage. Understanding of biodegradability in various environments and waste management systems is incomplete and remains an active area of scientific investigation and policy development.[26] Decomposition requires suitable environmental conditions of moisture, aeration, acidity etc., with additional food sources for the organisms causing the decomposition, and so will only occur at favourable rates under particular conditions. For example, a number of biodegradable plastics have been designed to break down rapidly in industrial composting systems under aerobic conditions (i.e. with oxygen available), typically alongside food and green waste. For such plastics to be defined as 'compostable' they must comply with standards such as EN 13432.[27] However, plastics that are compostable according to such standards do not necessarily break down in 'domestic' or 'yard' composting systems (typically those in householders' gardens in which the composting temperatures rarely exceed 40°C) nor in anaerobic digestion systems (i.e. in the absence of oxygen).

In general, standards for biodegradability specify breakdown performance under precise test conditions. Table 2 lists several types of plastic that meet some very specific definitions of biodegradability. Polylactic Acid (PLA)-based plastics illustrate the point that biodegradability under one set of conditions does not necessarily mean that breakdown will occur in other systems or other environmental conditions. This is particularly significant for the differences between the terrestrial, freshwater and marine environments, and for plastics that escape from containment in waste management systems to leak into the general environment where conditions are variable and can be unfavourable for their breakdown (e.g. hedgerows, deep oceans, dry terrestrial environments).

26 Patel and others (n 24); Miao Guo and Richard J Murphy, 'Is There a Generic Environmental Advantage for Starch–PVOH Biopolymers Over Petrochemical Polymers?' (2012) 20(4) Journal of Polymers and Environment 976; Tanja Narancic and others, 'Biodegradable Plastic Blends Create New Possibilities for End-of-Life Management of Plastics but they are not a Panacea for Plastic Pollution' (2018) 52(18) Environmental Science & Technology 10441; Juergen Puls, Steven A Wilson and Dirk Hölter, 'Degradation of Cellulose Acetate-Based Materials: A Review' (2011) 19 Journal of Polymers and Environment 152; Anonymous, Review of Standards for Biodegradable Plastic Carrier Bags (Department for Environment, Food and Rural Affairs 2015) <https://www.gov.uk/government/publications/carrier-bags-review-of-standards-for-biodegradable-plastic-bags>.

27 BS EN 13432 2000, 'Packaging - Requirements for packaging recoverable through composting and biodegradation: Test scheme and evaluation criteria for the final acceptance of packaging'. British Standards Institution, London, 2000.

Table 2. Examples of fossil and bio-based plastics showing their biodegradability characteristics under defined circumstances

(adapted from Song and others, Narancic and others, and Puls and others)[28]

Polymer / plastic	Non-biodegradable	Biodegradable: Industrial compost	Biodegradable: Domestic compost	Biodegradable: Anaerobic digestion
Fossil-based Polymers				
Polyethylene (PE)	Yes	X	X	X
Polypropylene (PP)	Yes	X	X	X
Polystyrene (PS)	Yes	X	X	X
Polycaprolactone (PCL)	X	Yes	Yes	?
Biomass-based polymers				
Polylactic Acid (PLA)	X	Yes	X	?
Bio-based PE	Yes	X	X	X
Starch (incl. blends)	X	Yes	Yes	Yes
Cellulose	X	Yes	Yes	Yes
Cellulose acetate*	X	Yes	?	Yes
Polybutylene succinate (PBS)	X	Yes	X	?

Yes = positive for the character **X** = negative for the character

? = unknown/uncertain (particularly for solid products rather than powders etc)

* highly dependent upon degree of acetyl group substitution (DS) on the cellulose; biodegradability is substantially reduced at DS above 2.[29]

Biodegradability is desirable for some applications and in some waste management systems. However, biodegradability is not a universal solution to the problem of pollution by plastics leaking into the unconfined environment. As noted, plastics classified as biodegradable generally only degrade under rather specific conditions, such as in industrial composting or anaerobic digestion facilities, and it cannot be assumed that they will degrade in uncontrolled natural environments.[30] Biodegradability can also be a disadvantage in landfill sites, where there is a risk of methane production and release from decomposing biodegradable plastics; a significant content of biodegradable plastic also extends the time period before a landfill site stabilises sufficiently for the land to be re-used. Furthermore, mixing biodegradable with non-degradable plastics in recycling systems reduces the performance and durability of the recyclate. For these reasons, an investigation carried out for the government of Sweden has recently counselled against

28 Jim Song and others, 'Biodegradable and Compostable Alternatives to Conventional Plastics' (2009) 364 Philosophical Transactions of the Royal Society B 2127; Naranic and others (n 26); Puls, Wilson and Hölter (n 26).

29 ibid.

30 Narancic and others (n 26).

regarding supposedly biodegradable plastics as a solution to plastic pollution.[31]

Bio-based plastics, as the name implies, are made from feedstocks of biological origin, typically from crops like corn, wheat, sugarcane or seed oils. As noted above, the feedstock from which a plastic is made does not determine whether it is biodegradable: bio-based plastics can be just as ‘durable’ as their fossil counterparts. The Green Polyethylene™ manufactured by Braskem is a good example as its polymer properties are identical to those of a fossil polyethylene. Table 2 underlines that biodegradable plastics can be manufactured from either bio-based feedstocks (corn, sugars, plant oils etc.) or from fossil resources (oil, gas), and in some cases can include blends of both types of feedstocks.

A fossil-based plastic burned or exposed to conditions under which it degrades aerobically releases fossil carbon dioxide (CO_2) which contributes to global warming. By contrast, combustion or aerobic decomposition of a bio-based plastic releases CO_2 which derives from the renewable carbon cycle and is therefore defined as climate-neutral. However, if the plastic is digested anaerobically, much of its carbon is released as methane (CH_4) which has a much larger greenhouse warming potential than CO_2. Rather than being released to the atmosphere, some or all of the methane may be captured and used as a fuel to generate useful heat and/or electricity by combustion to CO_2, displacing use of fossil fuels that would lead to release of fossil CO_2. Thus, from a climate-change perspective, the difference between fossil-based and bio-based plastics is not simple: it depends not only on the processing route (including how the feedstock for a bio-plastic is produced) but also on how the plastic is managed after use. Therefore, it cannot be assumed that a bio-based plastic has a more favourable environmental profile than a fossil-based equivalent. Following the life cycle approach, the entire product chain, from feedstock production (agriculture or forestry, or oil and gas production), processing into the plastic, use, through to eventual disposal and waste management, must be examined to reach an informed evaluation.

31 Åsa Stenmarck, *Det Går om vi Vill: Förslag till en Hållbar Plastanvändning* (‘We Can if we Want To: Proposals for Sustainable Use of Plastics’) (Statens Offentliga Utredningar SOU, Stockholm, 2018) 84.

3 PLASTIC POLLUTION

3.1 Principal Sources of Plastic Pollution

Figure 1 shows the principal points in the industrial ecology at which plastics ‘leak’ from the economy and are dissipated into the environment; i.e. the principal sources of plastic pollution.

In a few uses, products formed of or containing plastics are not just leakage-prone but are actually designed to be released into the environment (DR in Figure 1). These include microbeads and other materials, such as ‘glitter’ particles, currently incorporated in some cosmetic and body-care products, and also items such as balloons and confetti released in the course of popular celebrations. Microbeads in particular have been implicated as a major environmental problem because marine creatures may mistake them for food, with especially harmful consequences.[32]

Undesigned releases (UDR in Figure 1) represent a larger proportion of the leakages, and generally represent a more difficult problem for regulation to prevent plastic pollution. Substantial leakages (L in Figure 1) occur at early stages in product life cycles preceding the use phase, including spillages of plastic pellets during production and transport.[33] Losses of objects such as the strapping bands used in transport are also significant.[34]

32 Law (n 8); Mark Brownlow and James Honeyborne, ‘Blue Planet II’ Television Series (BBC 2017); Yooeun Chae and Youn-Joo An, ‘Effects of Micro-and Nanoplastics on Aquatic Ecosystems: Current Research Trends and Perspectives’ (2017) 124(2) Marine Pollution Bulletin 624.

33 Therese M Karlsson and others, ‘The Unaccountability Case of Plastic Pellet Production (2018) 129(1) Marine Pollution Bulletin 52.

34 OSPAR, OSPAR Intermediate Assessment 2017 - Beach Litter - Abundance, Composition and Trends (2017) <https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/pressures-human-activities/marine-litter/>.

Other undesigned releases are best described as litter: plastic items casually discarded after use so that they are carried by the wind and may enter waterways.[35] Plastic packaging is particularly implicated as a significant source of litter. While some packaging is legitimately considered non-essential (see below), plastic packaging cannot be eliminated from the economy because appropriate packaging is essential to avoid contamination and wastage of food and damage to other material products. Litter on land can be collected but this is extremely labour-intensive and may have a significant carbon footprint.[36] Passive traps to collect plastic litter from waterways appear to hold some promise, with the advantage that the plastics collected are not too contaminated or degraded and may be returned to the economy for chemical recycling or energy recovery.[37] However, it is more effective to cut off these releases at source; this approach is discussed further below.

3.2 Marine Debris

Plastic waste leaking into all environmental compartments tends to follow the natural environmental fluxes and so end up in the oceans unless it is trapped before getting that far. Beach surveys and measurements in the marine environment suggest that waste from marine commercial activities represents the largest fraction of marine macroplastic debris by weight, followed by debris from terrestrial sources, notably packaging and cigarette filters (cellulose acetate).[38] Microplastic debris such as textile fibres, microbeads and particles from tyre wear add to this loading.

The accumulation of plastic debris in the world's oceans is the most dramatic evidence of the problem of plastic pollution, attracting attention following publication in 2015 of a much-cited paper,[39] and highlighted in a popular television series.[40] That paper also pointed out that the debris enters the environment primarily from the 'Global South' where, especially in Asia, the quantities and proportions of mismanaged waste are orders of magnitude higher than in the industrial and post-industrial world. China emerged as much the greatest source of plastic marine debris, followed by Indonesia.[41] By contrast, if the coastal countries in the EU were considered collectively, they would have been numbered 18 in the ranking of countries generating plastic marine debris in 2015, comparable with Morocco and three places above the USA. Thus, plastic pollution in the oceans is as much a global problem as climate change and, even more than with climate change, measures to reduce this type of pollution must embrace the Global South as major players in the response. However, the origin of plastic material leaking from countries in the Global South bears closer examination. In 2015, the Western world was exporting large quantities of mixed waste plastic to the Global South, so that much of the marine debris entering the oceans originated in developed countries. Imports of mixed waste plastic into China have now been terminated,[42] and other Asian countries are introducing or considering similar bans.[43] This is

35 Laurent Lebreton and others, 'River Plastic Emissions to the World's Oceans' (2017) 8 Nature Communications 15611<https://www.nature.com/articles/ncomms15611>.

36 Isabel Cañete Vela, Options for Closing the Loop for Plastic Debris: Environmental Analysis of Beach Clean-Up and Waste Treatments (ESA Report, Environmental Systems Analysis, Chalmers University of Technology, Göteborg, Sweden, 2017) 4.

37 World Economic Forum, Guatemala's Biofences are Cleaning up Latin American Rivers, and it's Thanks to a Facebook Video (2018) <https://www.weforum.org/agenda/2018/12/guatemala-s-biofences-are-cleaning-up-latin-american-rivers-and-it-s-thanks-to-a-facebook-video/>; Katrien Steenmans, 'Plastic Waste: Floating Parks Made From it Could Unite Communities to Tackle Pollution' (*The Conversation*, 3 January 2019) <https://theconversation.com/plastic-waste-floating-parks-made-from-it-could-unite-communities-to-tackle-pollution-108229>; Jackie Snow, 'Googly-Eyed Trash Eaters may Clean a Harbor Near You' *National Geographic* (17 February 2017) <https://news.nationalgeographic.com/2017/02/mr-trash-wheels-professor-trash-wheels-baltimore-harbor-ocean-trash-pickup/>.

38 Anna Maria Addamo, Perrine Laroche and Georg Hanke, 'Top Marine Beach Litter Items in Europe: A Review and Synthesis Based on Beach Litter Data', EUR 29249 EN (Publications Office of the European Union, Luxembourg, 2017).

39 Jambeck and others (n 1).

40 Brownlow and Honeyborne (n 32).

41 Jambeck and others (n 1).

42 Costas Velis, Global Recycling Markets-Plastic Waste: A Story for One Player–China (International Solid Waste Association—Global Waste Management Task Force 2014) 1-66.

43 Steve Toloken, 'Vietnam, Malaysia Limit Plastic Scrap Imports' *Plastic News* (26 July 2018) <https://www.plasticsnews.com/article/20180726/NEWS/180729919/vietnam-malaysia-limit-plastic-scrap-imports>.

acting as a spur to change approaches to management of plastics in the industrialised world, to avoid an explosion in the quantities of plastic that are consigned to landfill or left unmanaged.[44]

Undesigned losses of plastics during use are a particular difficulty for demanding applications outside the urban or built environment, particularly in the marine sector. Direct leakages into the oceans arise from losses of fishing gear and of ship-borne cargo. These leakages represent economic losses to operators, so that there are already incentives to avoid them and it is difficult to conceive of regulatory measures that would curtail them beyond penalties for deliberately discarding damaged gear (see below). The source most difficult to cut off is likely to be fishing gear, because alternative materials are not available and duties are so arduous that some losses are inevitable. Fishing gear has been estimated to make up about 10 per cent of current marine debris,[45] so that eliminating the other sources would remove about 90 per cent of the flows of plastics into the oceans (although it would not remove the debris that has already accumulated). However, this does not correspond to removing 90 per cent of the problems arising from plastic pollution: fishing gear, together with balloons and plastic bags, is considered to be the waste most harmful to marine life.[46]

There is no doubt that the quantities of waste plastic in the oceans has already built up to worrying levels. The material is particularly concentrated in a few locations, known as the 'ocean gyres', but it is widespread and is found even in the most remote locations such as the Northern shoreline of Svalbard.[47] Unlike global climate change, where removal of climate-forcing gases from the atmosphere is unlikely ever to be practical,[48] it should be possible to collect some at least of the stock of marine debris. What can be done with it is more contentious. Even more than plastic litter collected on land and from fresh water, marine debris is inevitably mixed and contaminated with other materials, including salt. Therefore, mechanical or chemical recycling of marine debris is not feasible without careful sorting, cleaning and pre-treatment. Some processes have been developed to demonstrate recycling of marine plastic, but the quantities of material treated are nugatory; the operations are expensive and unlikely to be generally viable for such a low-value material. Usually, marine plastic is too contaminated even to be used as fuel without prohibitively expensive pre-treatment. Even material recovered in beach clean-ups is so dirty, salty and stringy that it must be sent to landfill,[49] as shown in Figure 1.

In a further parallel with climate change, the effects of marine pollution by plastics are felt in countries other than those where the emissions originate. Small island developing states (SIDS) are particularly vulnerable because the shoreline is important for the natural ecology and the economy.[50] The vulnerability is amplified by another feature of SIDS: the economy may be too small for recycling to be economically feasible - small island states rarely have the kind of processing and refining plant that could accept recycled hydrocarbons (see Figure 1). Furthermore, transport distances are too large for export of low-value materials to be viable. It therefore seems inevitable that marine plastic litter on SIDS must be consigned to landfill, although space with appropriate characteristics for a landfill is often scarce or unavailable. Thus, SIDS are doomed to be 'sinks' for persistent substances that arrive by environmental flows or imports.[51] Even if leakages of plastics into the oceans are prevented, management of plastics and marine plastic pollution will remain long-term problems for small island states in particular.

44 Gear (n 20).

45 Graeme MacFadyen, T Huntington and R Cappell, 'Abandoned, Lost or Otherwise Discarded Fishing Gear' (UNEP Regional Seas Reports and Studies No. 185, 2009).

46 Chris Wilcox and others, 'Using Expert Elicitation to Estimate the Impacts of Plastic Pollution on Marine Wildlife' (2016) 65 Marine Policy 107.

47 Henrikke Baumann (Kiteki), Video: Reversing the Flows <https://vimeo.com/171651682>.

48 Colin L Pritchard and others, 'Thermodynamics, Economics and Systems Thinking: What Role for Air Capture of CO_2?' (2015) 94 Process Safety and Environmental Protection 188.

49 Cañete Vela (n 36).

50 Florina Lachmann and others, Marine Plastic Litter on Small Island Developing States (SIDS): Impacts and Measures (Swedish Institute for the Marine Environment, Report No.4, 2017).

51 Vimi Dookhun, Assessing Environmental Risks Associated with Persistent Toxic Substances in Mauritius: The Case of Mercury (PhD Thesis, University of Mauritius 2016).

3.3 A Systematic Basis For Regulation and Action

The analysis of the uses of plastics and sources of releases into the environment summarised in Figure 1 provides a basis for a systematic and comprehensive approach to curtailing plastic pollution. Table 1 summarises the waste management activities to be promoted to increase the 'circularity' of the economy for plastics. The widespread move towards banning single-use plastic items is also intended to promote circularity. These measures should have some effect in reducing emissions of plastics by reducing the total quantities of plastic entering use and providing economic incentives to retain plastics within the economy. However, increasing circularity will not, as has been suggested,[52] be sufficient on its own to eliminate further plastic pollution completely: action to eliminate plastic pollution must target the losses of leakage-prone items from the economy shown in Figure 1.

Designed Releases (DR in Figure 1) are an obvious target for regulation. Many of these uses are legitimately regarded as non-essential. As a specific example, following bans by some local authorities, Norway has banned the release of helium-filled balloons, a previously popular activity particularly in celebrations on the national day.[53] Plastics in consumer products like cosmetics and personal care products, designed for the plastic to be dispersed into the environment, are also obvious targets for elimination or replacement.

Undesigned Releases (UDR in Figure 1) present a different kind of problem requiring different approaches. Many undesigned releases are associated with packaging. To eliminate these, it is necessary to redesign not only the packaging but also the delivery and collection systems. Some delivery and distribution companies are turning to re-usable or rented packaging, an example of the general move away from single-use plastic items. Reusable and foldable plastic transport crates are used in many countries, notably in delivery chains from agricultural producers to shops for fruit and vegetables, and on to consumers. They belong to fleet managers, are easy to clean and repair (by changing broken components) and protected by a deposit - i.e. they have a value and an owner. There are attempts to extend this approach to containers to distribute liquids using standardised container shapes and materials, although preference is given to metal rather than plastic containers.[54]

Other undesigned releases result from leakage-prone items such as take-away packaging and consumer items such as bags, cups and drinking straws. In some convenience uses, conventional plastics may be substituted by biodegradable materials, including paper and other vegetable fibres as well as biodegradable plastics. However, the scope for replacement of conventional plastics throughout the economy is limited. Furthermore, as noted above, substituting plastics by cotton, e.g. for bags, comes at the expense of increasing consumption of non-renewable resources and use of land for agricultural production. Much plastic litter results from unthinking human action. Therefore, it is essential to modify the behaviour that leads to consumer litter, through education or persuasion reinforced by applying penalties for littering. Appropriate waste collection and packaging design are also needed General elimination of single-use consumer items is primarily a move to prevent casual littering as a source of leakages; i.e. it is primarily intended to rectify the consequences of human behaviour. However, to be effective, moves to eliminate single-use plastics should target the most leakage-prone items.

A notable example is drinking water contained in plastic bottles. Bottled potable water has an important role in some circumstances, primarily in disaster relief or where potable water is not available. However, for general consumer convenience in the developed world, it represents another non-essential use. Some municipalities and local governments have promoted

52 Rhodes (n 8); Patrick ten Brink and others, Circular Economy Measures to Keep Plastics and Their Value in the Economy, Avoid Waste and Reduce Marine Litter (Kiel Institute for the World Economy, Economics Discussion Papers No. 2018-3, 2018) <http://www.economics-journal.org/economics/discussionpapers/2018-3>; A Löhr and others, 'Solutions for Global Marine Litter Pollution' (2017) 28 Current Opinion in Environmental Sustainability 90.

53 'Bans Imposed on Helium Balloons' *News in English* (17 April 2018) <https://www.newsinenglish.no/2018/04/17/bans-imposed-on-helium-balloons/>.

54 This is the idea behind Loop, focusing on reduce, reuse and recycle. For more information, see <https://loopstore.com>.

campaigns against the sale of pre-bottled water, with consumers encouraged instead to use multiple-use containers filled from the piped supply of potable water. Some institutions have gone further and banned sales of pre-bottled water on their premises. Eliminating pre-bottled water has the additional advantage that the environmental impacts of piping water are much lower than delivering it in bottles. For consumers who prefer carbonated water, the approach of adding the carbon dioxide to piped water also has environmental advantages in addition to replacing the plastic bottle by a multi-use container.

Deposit-return schemes provide a superficially obvious way to incentivise behaviour change and reduce littering: the consumer pays a charge on a packaged item which is refunded if the packaging is returned. If returned packages, such as bottles, can be returned to the original packager, there is a possibility of moving from single-use to multiple-use packaging. However, the consequences can be perverse, especially if the packaging is not readily recyclable or reusable, or if there is no direct route back to the original supplier. As an egregious example, South Africa's plastic recovery rate is higher than in Europe but so is the leakage of mismanaged waste.[55] Even if there is a direct and leak-free return route, there are further potential problems in promoting re-use rather than recycling, as noted earlier. Sorting returned bottles and routing them back to the original packager entails significant expense. Furthermore, the bottles themselves need to be robust, usually with thicker walls than single-use items and sometimes with reinforcing sashes or ribs. The additional weight tends to offset re-use so that the objective of reducing the flow of plastics through the economy is thwarted.

The measures outlined above address mainly terrestrial leakages of plastic that then finds its way into the oceans. However, as noted above, much ocean plastic arises from commercial marine activities and is more difficult to regulate. One possible approach is to provide economic incentives for companies to retain damaged gear, analogous to terrestrial deposit/return systems, combined with better provision of facilities in ports for disposal of damaged gear. Iceland has introduced a system under which fishing companies may waive their (substantial) fee to the national recycling system upon return of nets;[56] similar approaches are being trialled in other countries. Fishing nets are made primarily of nylon with other materials for specific components. A chemical recycling route is developing in which nylon threads, mainly from fishing nets, are used to make recycled products such as carpets.[57]

Waste plastic already in the oceans would remain even if measures to eliminate further 'leakage' were rapid and effective. Given the durability of much of the plastic waste and the well-documented environmental damage it causes, there is a strong case for clean-up of seas and shorelines. The problem is global and requires international action. The waste already in the oceans cannot currently be used for any economic benefit, and ways to recycle a significant part of the existing waste are still remote aspirations. For the foreseeable future, material recovered must be disposed of in terrestrial landfills, representing an economic cost. Specific states and jurisdictions have some economic stake in cleaning up their own shorelines. However, waste already dispersed in the oceans represents pollution of the global commons, even though it may eventually wash up on someone's shoreline. We cannot avoid the conclusion that efforts to remove polluting plastics from the world's oceans will require an international initiative with dedicated resources.

4 CONCLUSIONS

Any aspiration to remove plastics completely from the economy is unrealistic. Similarly, wholesale

55 Harro von Blottnitz, Takunda Chitaka and Clare Rodseth, 'South Africa Beats Europe at Plastics Recycling, but also is a Top 20 Ocean Polluter, Really?' *LinkedIn Pulse* (3 September 2018) <https://www.linkedin.com/pulse/south-africa-beats-europe-plastics-recycling-also-top-von-blottnitz/>.

56 Information on Fisheries Management in the Republic of Iceland <http://www.fao.org/fi/oldsite/FCP/en/ISL/body.htm>; Guðlaugur Gylfi Sverrisson, Icelandic System for Fishing Nets (Conference on Plastics in the Marine Environment, Reykjavik, 24 September 2014) <https://www.ust.is/library/Skrar/Einstaklingar/Vatnsgaedi/Plastradstefna/7_Gudlaugur_Sverrisson.pdf>.

57 Aquafil Global Official Website: <https://www.aquafil.com>.

replacement of durable by biodegradable plastics is not a panacea, or even a realistic or attractive approach. Moving towards 'circular' use will have some effect in reducing the leakage of plastics from the economy into the unconfined environment, which is the source of plastic pollution, but requires changes in commercial practices as well as in plastic products and materials. The highest priority is to focus on preventing leakage by ensuring that all plastic materials remain within the economy. Analysis of the industrial ecology of plastics shows where the main leakages arise, and thereby shows where regulatory attention should be directed (Figure 1). Table 1 summarises the options available to manage plastics at different points within the economy. Regulatory approaches need to recognise the different types of plastics and ensure that used plastic products are directed to the appropriate route for re-use, recycling or disposal.

Particularly for marine debris, efforts to reduce the flows of plastics into the environment must be undertaken worldwide, involving the Global South, so that international action and agreement are essential. In addition to measures to reduce 'leakage' of waste plastic, the stock of polluting plastics already in the oceans demands an international clean-up effort, recognising that recovered plastic debris will have to be consigned to landfill and therefore has no economic value.

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