ELLEN MACARTHUR FOUNDATION

THE NEW PLASTICS ECONOMY

RETHINKING THE FUTURE OF PLASTICS

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PREFACE

The circular economy is gaining growing attention as a potential way for our society to increase prosperity, while reducing demands on finite raw materials and minimising negative externalities. Such a transition requires a systemic approach, which entails moving beyond incremental improvements to the existing model as well as developing new collaboration mechanisms.

The report explores the intersection of these two themes, for plastics and plastic packaging in particular: how can collaboration along the extended global plastic packaging production and after-use value chain, as well as with governments and NGOs, achieve systemic change to overcome stalemates in today's plastics economy in order to move to a more circular model?

The New Plastics Economy aims to set an initial direction and contribute to the evidence base by synthesising information from across many dispersed sources. It assesses the benefits and drawbacks of plastic packaging today, and makes the case for rethinking the current plastics economy. It lays out the ambitions and benefits of the New Plastics Economy — a system aiming to achieve drastically better economic and environmental outcomes. It proposes a new approach and action plan to get there.

The report's objective is not to provide final answers or recommendations. Rather, it aims to bring together for the first time a comprehensive global perspective of the broader plastic packaging economy, present a vision and propose a roadmap as well as a vehicle for progressing this roadmap, and providing a much needed global focal point to carry this agenda forward. This report also identifies a number of significant knowledge gaps and open questions that need to be further explored.

This report is the product of Project MainStream, an initiative that leverages the convening power of the World Economic Forum, the circular economy innovation capabilities of the Ellen MacArthur Foundation, and the analytical capabilities of McKinsey & Company. We are grateful to our numerous partners and advisors for their insights and support throughout this project, and the Project MainStream Steering Board for their continued collaboration on the transition towards a circular economy.

For the three institutions that have launched the MainStream initiative, this report is an encouragement to continue to foster cross-industry collaboration as a major avenue to accelerate the transition to the much-needed circular economy. We hope you find this report informative and useful. We invite you to engage with us on this timely opportunity.

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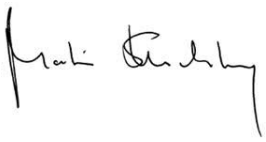

FOREWORD

H. E. Mogens Lykketoft
President of the UN General Assembly for the 70th session

We live in a defining moment in history — a moment where the international community has come together to agree on an ambitious framework to resolve some of the world's most daunting challenges.

Anchored in a set of universally applicable Sustainable Development Goals, the 2030 Agenda for Sustainable Development, adopted by all 193 members of the United Nations in September 2015, underlined a common determination to take bold and transformative steps towards a better future for all.

Now is the time for implementation. We must now begin to practise what we have preached — changing our production and consumption patterns in order to create virtuous cycles rather than depletive ones and harnessing the global interconnectedness, communications technology and breakthroughs in materials science.

All sectors of the economy must respond to these global agreements, and due to their sheer pervasiveness and scale, some sectors are facing questions as to the direction they should take. This is particularly the case for plastics, which have tangible and substantial benefits, but whose drawbacks are significant, long-term and too obvious to ignore. It is therefore very encouraging to see an initiative like the New Plastics Economy take shape, supported by a diverse group of participants from the industry striving for innovative solutions grounded in systems thinking.

Concrete and game-changing steps have to be taken for us to achieve the future we want anchored in the SDGs. I therefore welcome wholeheartedly the bold ideas, ambitious objectives and comprehensive action plan presented in this report. If implemented, it could make an important contribution to transforming this important sector of the global economy.

IN SUPPORT OF THE NEW PLASTICS ECONOMY

'As the Consumer Goods Forum, we welcome this groundbreaking report on the New Plastics Economy. Packaging is integral to the delivery of safe, high-quality consumer products, but we recognise the need to rethink radically how we use plastics, creating new circular systems that conserve resources, reduce pollution and promote efficiency. This report improves substantially our understanding of the solutions we need.'

MIKE BARRY AND JEFF SEABRIGHT
CO-CHAIRS OF THE CONSUMER GOODS
FORUM SUSTAINABILITY PILLAR

'The Global Ocean Commission has been working with the Prince of Wales' International Sustainability Unit to raise political and business awareness of the urgent need to address plastic waste entering the ocean, and transition to a more circular model for plastics. I am very pleased to see that the Ellen MacArthur Foundation and its partners have responded to this call to action, through the New Plastics Economy report, and have developed an ambitious yet realistic plan to address the issue at its root. I strongly encourage nations and business leaders to consider the contents of this report and develop corresponding strategies.'

DAVID MILIBAND
CO-CHAIR
GLOBAL OCEAN COMMISSION

'It is high time to implement the circular economy principles in the plastic sector. Increasing plastic recycling would capture significant material value and help reduce greenhouse gas emissions. As pointed out in this report, plastic production has increased from 15 million tonnes in the sixties to 311 million tonnes in 2014 and is expected to triple by 2050, when it would account for 20% of global annual oil consumption. These are exactly the reasons why Veolia, which is already actively engaged in promoting circular solutions, welcomes and supports the New Plastics Economy.'

ANTOINE FRÉROT
CEO
VEOLIA

'Plastic products and packaging have an undeniably important role in our society. Plastic waste should not. Not only does plastic waste pollute our land and ocean — to the detriment of wildlife and humans — but the loss of plastic from the current plastic economy is an economic drain. Plastic waste is a problem we can solve and need to solve now. And the solutions are many. Near term benefits will be made by better waste management and less use, especially single use, of plastic. But ultimately this problem requires a circular economy approach, where used plastic becomes a feedstock rather than a waste. There has never been more political will and technical ability to solve our plastic waste problem. Together we can stem the tide of plastic waste suffocating our ocean. Together we can change the world — and save our ocean.'

CATHERINE NOVELLI
U.S. UNDER SECRETARY OF STATE FOR
ECONOMIC GROWTH, ENERGY AND THE ENVIRONMENT

'The New Plastics Economy takes a detailed look into one of the world's most pervasive modern materials. The report lays out a foundation for a more sustainable system of making and using plastics and plastic packaging, taking into account the unique challenges and opportunities on the use, reuse, and collection of the material. It is a call to action for an ambitious redesign with a longer term view of the value at stake and intensive collaboration among various players.'

DOMINIC BARTON
GLOBAL MANAGING DIRECTOR
MCKINSEY & COMPANY

‘London is already actively taking steps towards a more circular model for plastics and plastic packaging. However more can and needs to be done, and I therefore welcome, support and thank the Ellen MacArthur Foundation, the World Economic Forum and McKinsey for their effort in identifying and promoting the global innovations required if we are going to continue to enjoy the benefits that plastics bring to our lives.’

MATTHEW PENCHARZ
DEPUTY MAYOR FOR ENVIRONMENT AND ENERGY
GREATER LONDON AUTHORITY

‘The New Plastics Economy is an exciting opportunity to inspire a generation of designers to profoundly rethink plastic packaging and its role in a system that works.’

TIM BROWN
CEO
IDEO

‘In the Global Ocean Commission’s report *From Decline to Recovery: A Rescue Package for the Global Ocean*, we identified keeping plastics out of the ocean as one of our key proposals for action to advance ocean recovery. This report is an excellent next step, offering a root-cause solution to the problem of ocean plastics as part of a broader rethink and new approach to capture value in the New Plastics Economy. The economic and environmental case is now clear — I therefore call on governments and businesses alike to take urgent action to capture the opportunity.’

TREVOR MANUEL
CO-CHAIR
GLOBAL OCEAN COMMISSION

‘SUEZ was pleased to contribute to the New Plastics Economy report, a collaborative case for rethinking the current plastics economy. As this report shows, a radical and joint rethink of both design and after-use processes will be required, in addition to other measures such as stimulating demand for secondary raw materials. We look forward to continued collaboration to enable better economic and environmental results in the plastic packaging value chain and to accelerate the transition towards the circular economy.’

JEAN-LOUIS CHAUSSADE
CHIEF EXECUTIVE OFFICER
SUEZ

‘Systems thinking and integrated approaches are needed if we are to sustainably use and manage our global resources in a manner that enables the achievement of the Paris climate change agreement while advancing a circular economy. In my work with the G7 Alliance on Resource Efficiency, there’s ongoing discussion about the need to disrupt “business as usual”. *The New Plastics Economy — Rethinking the future of plastics* continues in that vein.’

MATHY STANISLAUS
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FOR THE OFFICE OF LAND AND EMERGENCY MANAGEMENT

‘This is an important report highlighting some of the key issues related to plastics and their leakage into the marine environment. It is also an exciting report that proposes new approaches within a circular economy framework that could re-orientate society’s use of plastics and start to address the problems that our current use is creating.’

PROFESSOR STEPHEN DE MORA
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‘At Desso we are proud to have been part of developing the New Plastics Economy report, a result of Project MainStream, one of the first cross-industry collaborations of its kind. The report shows how companies — through collaboration, vision and clear research — can build a foundation for a truly circular model for plastics.’

ROLAND JONKHOFF
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This report was written under the umbrella of Project MainStream, a multi-industry, global initiative launched in 2014 by the World Economic Forum and the Ellen MacArthur Foundation, with McKinsey & Company as knowledge partner. MainStream is led by the chief executive officers of nine global companies: Averda, BT, Desso BV (a Tarkett company), Royal DSM, Ecolab, Indorama, Philips, SUEZ and Veolia.

MainStream aims to accelerate business-driven innovations and help scale the circular economy. It focuses on systemic stalemates in global material flows that are too big or too complex for an individual business, city or government to overcome alone, as well as on enablers of the circular economy such as digital technologies.

DISCLAIMER

This report has been produced by a team from the Ellen MacArthur Foundation, which takes full responsibility for the report's contents and conclusions. McKinsey & Company provided analytical support. While the project participants, members of the advisory panel and experts consulted acknowledged on the following pages have provided significant input to the development of this report, their participation does not necessarily imply endorsement of the report's contents or conclusions.

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EXECUTIVE SUMMARY

Plastics have become the ubiquitous workhorse material of the modern economy — combining unrivalled functional properties with low cost. Their use has increased twenty-fold in the past half-century and is expected to double again in the next 20 years. Today nearly everyone, everywhere, every day comes into contact with plastics — especially plastic packaging, the focus of this report.

While delivering many benefits, the current plastics economy has drawbacks that are becoming more apparent by the day. After a short first-use cycle, 95% of plastic packaging material value, or USD 80–120 billion annually, is lost to the economy. A staggering 32% of plastic packaging escapes collection systems, generating significant economic costs by reducing the productivity of vital natural systems such as the ocean and clogging urban infrastructure. The cost of such after-use externalities for plastic packaging, plus the cost associated with greenhouse gas emissions from its production, is conservatively estimated at USD 40 billion annually — exceeding the plastic packaging industry's profit pool. In future, these costs will have to be covered. In overcoming these drawbacks, an opportunity beckons: enhancing system effectiveness to achieve better economic and environmental outcomes while continuing to harness the many benefits of plastic packaging. The 'New Plastics Economy' offers a new vision, aligned with the principles of the circular economy, to capture these opportunities.

With an explicitly systemic and collaborative approach, the New Plastics Economy aims to overcome the limitations of today's incremental improvements and fragmented initiatives, to create a shared sense of direction, to spark a wave of innovation and to move the plastics value chain into a positive spiral of value capture, stronger economics, and better environmental outcomes. This report outlines a fundamental rethink for plastic packaging and plastics in general; it offers a new approach with the potential to transform global plastic packaging materials flows and thereby usher in the New Plastics Economy.

BACKGROUND TO THIS WORK

This report presents a compelling opportunity to increase the system effectiveness of the plastics economy, illustrated by examples from the plastic packaging value chain. The vision of a New Plastics Economy offers a new way of thinking about plastics as an effective global material flow, aligned with the principles of the circular economy.

The New Plastics Economy initiative is, to our knowledge, the first to have developed a comprehensive overview of global plastic packaging material flows, assessed the value and benefits of shifting this archetypally linear sector to a circular economic model, and identified a practical approach to enabling this shift. This report bases its findings on interviews with over 180 experts and on analysis of over 200 reports.

This report is the result of a three-year effort led by the Ellen MacArthur Foundation, in partnership with the World Economic Forum and supported by McKinsey & Company. Initial interest in the topic of packaging was stimulated by the second *Towards the Circular Economy* report developed by the Ellen MacArthur Foundation and published in 2013. That report quantified the economic value of shifting to a circular economic approach in the global, fast-moving consumer goods sector, highlighting the linear consumption pattern of that sector, which sends goods worth over USD 2.6 trillion annually to the world's landfills and incineration plants. The report showed that shifting to a circular model could generate a USD 706 billion economic opportunity, of which a significant proportion is attributable to packaging.

The subsequent *Towards the Circular Economy* volume 3, published by the Ellen MacArthur Foundation and the World Economic Forum in 2014, and again supported by McKinsey, explored the opportunities and challenges for the circular economy across global supply chains, focusing on several sectors — including plastic packaging. This study triggered the creation of Project MainStream, which formed material-specific working groups, including a plastics working group; this group in turn quickly narrowed its scope of investigation to plastic packaging due to its omnipresence in daily life all over the globe. The resulting initiative was the first of its type and included participants from across the global plastic packaging value chain. It sought to develop a deep understanding of global plastic packaging material flows and to identify specific ways of promoting the emergence of a new, circular economic model. It was led by a steering board of nine CEOs and included among its participants polymer manufacturers; packaging producers; global brands; representatives of major cities focused on after-use collection; collection, sorting and reprocessing/recycling companies; and a variety of industry experts and academics.

In the course of the MainStream work, an additional key theme presented itself: plastics 'leaking' (escaping) from after-use collection systems and the resulting degradation of natural systems, particularly the ocean. Although not the focal point initially, evidence of the looming degradation of marine ecosystems by plastics waste, particularly plastic packaging, has made plastics leakage a priority topic for MainStream. The economic impact of marine ecosystem degradation is only just being established through scientific and socio-economic research and analysis. However, initial findings indicate that the presence of hundreds of millions of tonnes of plastics (of which estimates suggest that packaging represents the majority) in the ocean, whether as microscopic particles or surviving in a recognisable form for hundreds of years, will have profoundly negative effects on marine ecosystems and the economic activities that depend on them.

This report is designed to initiate — not conclude — a deeper exploration of the New Plastics Economy. It provides an initial fact-base, shared language, and sense of the opportunities derived from the application of circular principles, and a plan for concerted action for the next three years and beyond. It also identifies critical questions that could not be answered sufficiently within the scope of this work, but need to be in order to trigger aligned action.

THE CASE FOR RETHINKING PLASTICS, STARTING WITH PACKAGING

Plastics and plastic packaging are an integral and important part of the global economy. Plastics production has surged over the past 50 years, from 15 million tonnes in 1964 to 311 million tonnes in 2014, and is expected to double again over the next 20 years, as plastics come to serve increasingly many applications. Plastic packaging, the focus of this report, is and will remain the largest application; currently, packaging represents 26% of the total volume of plastics used. Plastic packaging not only delivers direct economic benefits, but can also contribute to increased levels of resource productivity — for instance, plastic packaging can reduce food waste by extending shelf life and can reduce fuel consumption for transportation by bringing packaging weight down.

While delivering many benefits, the current plastics economy also has important drawbacks that are becoming more apparent by the day.

Today, 95% of plastic packaging material value, or USD 80–120 billion annually, is lost to the economy after a short first use. More than 40 years after the launch of the first universal recycling symbol, only 14% of plastic packaging is collected for recycling. When additional value losses in sorting and reprocessing are factored in, only 5% of material value is retained for a subsequent use. Plastics that do get recycled are mostly recycled into lower-value applications that are not again recyclable after use. The recycling rate for plastics in general is even lower than for plastic packaging, and both are far below the global recycling rates for paper (58%) and iron and steel (70–90%). In addition, plastic packaging is almost exclusively single-use, especially in business-to-consumer applications.

Plastic packaging generates significant negative externalities, conservatively valued by UNEP at USD 40 billion and expected to increase with strong volume growth in a business-as-usual scenario. Each year, at least 8 million tonnes of plastics leak into the ocean — which is equivalent to dumping the contents of one garbage truck into the ocean every minute. If no action is taken, this is expected to increase to two per minute by 2030 and four per minute by 2050. Estimates suggest that plastic packaging represents the major share of this leakage. The best research currently available estimates that there are over 150 million tonnes of plastics in the ocean today. In a business-as-usual scenario, the ocean is expected to contain 1 tonne of plastic for every 3 tonnes of fish by 2025, and by 2050, more plastics than fish (by weight).

The production of plastics draws on fossil feedstocks, with a significant carbon impact that will become even more significant with the projected surge in consumption. Over 90% of plastics produced are derived from virgin fossil feedstocks. This represents, for all plastics (not just packaging), about 6% of global oil consumption, which is equivalent to the oil consumption of the global aviation sector. If the current strong growth of plastics usage continues as expected, the plastics sector will account for 20% of total oil consumption and 15% of the global annual carbon budget by 2050 (this is the budget that must be adhered to in order to achieve the internationally accepted goal to remain below a 2°C increase in global warming). Even though plastics can bring resource efficiency gains during use, these figures show that it is crucial to address the greenhouse gas impact of plastics production and after-use treatment.

Plastics often contain a complex blend of chemical substances, of which some raise concerns about potential adverse effects on human health and the environment. While scientific evidence on the exact implications is not always conclusive, especially due to the difficulty of assessing complex long-term exposure and compounding effects, there are sufficient indications that warrant further research and accelerated action.

There are many innovation and improvement efforts that show potential, but to date these have proved to be too fragmented and uncoordinated to have impact at scale. Today's plastics economy is highly fragmented. The lack of standards and coordination across the value chain has allowed a proliferation of materials, formats, labelling, collection schemes, and sorting and reprocessing systems, which collectively hamper the development of effective markets. Innovation is also fragmented. The development and introduction of new packaging materials and formats across global supply and distribution chains is happening far faster than and is largely disconnected from the development and deployment of corresponding after-use systems and infrastructure. At the same time, hundreds, if not thousands, of small-scale local initiatives are launched each year, focused on areas such as improving collection schemes and installing new sorting and reprocessing technologies. Other issues, such as the fragmented development and adoption of labelling standards, hinder public understanding and create confusion.

In overcoming these drawbacks, an opportunity beckons: using the plastics innovation engine to move the industry into a positive spiral of value capture, stronger economics, and better environmental outcomes.

THE NEW PLASTICS ECONOMY: CAPTURING THE OPPORTUNITY

The overarching vision of the New Plastics Economy is that plastics never become waste; rather, they re-enter the economy as valuable technical or biological nutrients. The New Plastics Economy is underpinned by and aligns with principles of the circular economy. Its ambition is to deliver better system-wide economic and environmental outcomes by creating an effective after-use plastics economy, drastically reducing the leakage of plastics into natural systems (in particular the ocean) and other negative externalities; and decoupling from fossil feedstocks.

Even with today's designs, technologies and systems, these ambitions can already be at least partially realised. One recent study found, for example, that in Europe today 53% of plastic packaging could be recycled economically and environmentally effectively. While the exact figure can be debated and depends on, amongst others, the oil price, the message is clear: there are pockets of opportunities to be captured today — and even where not entirely feasible today, the New Plastics Economy offers an attractive target state for the global value chain and governments to collaboratively innovate towards.

Given plastic packaging's many benefits, both the likelihood and desirability of an across-the-board drastic reduction in the volume of plastic packaging used is clearly low. Nevertheless, reduction should be pursued where possible and beneficial, by dematerialising, moving away from single-use as the default, and substituting by other materials.

CREATE AN EFFECTIVE AFTER-USE PLASTICS ECONOMY.

Creating an effective after-use plastics economy is the cornerstone of the New Plastics Economy and its first priority. Not only is it crucial to capture more material value and increase resource productivity, it also provides a direct economic incentive to avoid leakage into natural systems and will help enable the transition to renewably sourced feedstock by reducing the scale of the transition.

- **Radically increase the economics, quality and uptake of recycling.** Establish a cross-value chain dialogue mechanism and develop a Global Plastics Protocol to set direction on the redesign and convergence of materials, formats, and after-use systems to substantially improve collection, sorting and reprocessing yields, quality and economics, while allowing for regional differences and continued innovation. Enable secondary markets for recycled materials through the introduction and scale-up of matchmaking mechanisms, industry commitments and/or policy interventions. Focus on key innovation opportunities that have the potential to scale up, such as investments in new or improved materials and reprocessing technologies. Explore the overall enabling role of policy.

- **Scale up the adoption of reusable packaging** within business-to-business applications as a priority, but also in targeted business-to-consumer applications such as plastic bags.

- **Scale up the adoption of industrially compostable plastic packaging for targeted applications** such as garbage bags for organic waste and food packaging for events, fast food enterprises, canteens and other closed systems, where there is low risk of mixing with the recycling stream and where the pairing of a compostable package with organic contents helps return nutrients in the contents to the soil.

DRASTICALLY REDUCE THE LEAKAGE OF PLASTICS INTO NATURAL SYSTEMS AND OTHER NEGATIVE EXTERNALITIES.

Achieving a drastic reduction in leakage would require joint efforts along three axes: improving after-use infrastructure in high-leakage countries, increasing the economic attractiveness of keeping materials in the system and reducing the negative impact of plastic packaging when it does escape collection and reprocessing systems. In addition, efforts related to substances of concern could be scaled up and accelerated.

- **Improve after-use collection, storage and reprocessing infrastructure in high-leakage countries**. This is a critical first step, but likely not sufficient in isolation. As discussed in the Ocean Conservancy's 2015 report *Stemming the Tide*, even under the very best current scenarios for improving infrastructure, leakage would only be stabilised, not eliminated, implying that the cumulative total volume of plastics in the ocean would continue to increase strongly. Therefore, the current report focuses not on the urgently needed short-term improvements in after-use infrastructure in high-leakage countries but rather on the complementary actions required.

- **Increase the economic attractiveness of keeping materials in the system.** Creating an effective after-use plastics economy as described above contributes to a root-cause solution to leakage. Improved economics make the build-up of after-use collection and reprocessing infrastructure more attractive. Increasing the value of after-use plastic packaging reduces the likelihood that it escapes the collection system, especially in countries with an informal waste sector.

- **Steer innovation investment towards creating materials and formats that reduce the negative**

environmental impact of plastic packaging leakage. Current plastic packaging offers great functional benefits, but it has an inherent design failure: its intended useful life is typically less than one year; however, the material persists for centuries, which is particularly damaging if it leaks outside collection systems, as happens today with 32% of plastic packaging. The efforts described above will reduce leakage, but it is doubtful that leakage can ever be fully eliminated — and even at a leakage rate of just 1%, about 1 million tonnes of plastic packaging would escape collection systems and accumulate in natural systems each year. The ambitious objective would be to develop 'bio-benign' plastic packaging that would reduce the negative impacts on natural systems when leaked, while also being recyclable and competitive in terms of functionality and costs. Today's biodegradable plastics rarely measure up to that ambition, as they are typically compostable only under controlled conditions (e.g. in industrial composters). Further research and game-changing innovation are needed.

- Scale up existing efforts to understand the potential impact of substances raising concerns and to accelerate development and application of safe alternatives.

DECOUPLE PLASTICS FROM FOSSIL FEEDSTOCKS.

Decoupling plastics from fossil feedstocks would allow the plastic packaging industry to complement its contributions to resource productivity during use with a low-carbon production process, enabling it to effectively participate in the low-carbon world that is inevitably drawing closer. Creating an effective after-use economy is key to decoupling because it would, along with dematerialisation levers, reduce the need for virgin feedstock. Another central part of this effort would be the development of renewably sourced materials to provide the virgin feedstock that would still be required to compensate for remaining cycle losses, despite the increased recycling and reuse.

THE NEW PLASTICS ECONOMY DEMANDS A NEW APPROACH

To move beyond small-scale and incremental improvements and achieve a systemic shift towards the New Plastics Economy, existing improvement initiatives would need to be complemented and guided by a concerted, global, systemic and collaborative initiative that matches the scale of the challenge and the opportunity. An independent coordinating vehicle would be needed to drive this initiative. It would need to be set up in a way that recognises that the innovations required for the transition to the New Plastics Economy are driven collaboratively across industry, cities, governments and NGOs. In this initiative, consumer goods companies, plastic packaging producers and plastics manufacturers would play a critical role, because they determine what products and materials are put on the market. Cities control the after-use infrastructure in many places and are often hubs for innovation. Businesses involved in collection, sorting and reprocessing are an equally critical part of the puzzle. Policymakers can play an important role in enabling the transition by realigning incentives, facilitating secondary markets, defining standards and stimulating innovation. NGOs can help ensure that broader social and environmental considerations are taken into account. Collaboration would be required to overcome fragmentation, the chronic lack of alignment between innovation in design and after-use, and lack of standards, all challenges that must be resolved in order to unlock the New Plastics Economy.

The coordinating vehicle would need to bring together the different actors in a cross-value chain dialogue mechanism and drive change by focusing on efforts with compounding effects that together would have the potential to shift the global market. Analysis to date indicates that the initial areas of focus could be:

ESTABLISH THE GLOBAL PLASTICS PROTOCOL AND COORDINATE LARGE-SCALE PILOTS AND DEMONSTRATION PROJECTS. Redesign and converge materials, formats and after-use systems, starting by investigating questions such as:

To what extent could plastic packaging be designed with a significantly smaller set of material/additive combinations, and what would be the economic benefits if this were done?

What would be the potential to design out small-format/low-value plastic packaging such as tear-offs, with challenging after-use economics and especially likely to leak?

What would be the economic benefits if all plastic packaging had common labelling and chemical marking, and these were well aligned with standardised separation and sorting systems?

What if after-use systems, currently shaped by fragmented decisions at municipal or regional level, were rethought and redesigned to achieve optimal scale and economics?

What would be the best levers to stimulate the market for recycled plastics?

Set global direction by answering such questions, demonstrate solutions at scale with large-scale pilots and demonstration projects, and drive global convergence (allowing for continued innovation and regional variations) towards the identified designs and systems with proven economics in order to overcome the existing fragmentation and to fundamentally shift after-use collection and reprocessing economics and market effectiveness.

MOBILISE LARGE-SCALE 'MOON SHOT' INNOVATIONS. The world's leading businesses, academics and innovators would be invited to come together and define 'moon shot' innovations: focused, practical initiatives with a high potential for significant impact at scale. Areas to look at for such innovations could include the development of bio-benign materials; the development of materials designed to facilitate multilayer reprocessing, such as the use of reversible adhesives based on biomimicry principles; the search for a 'super-polymer' with the functionality of today's polymers and with superior recyclability; chemical marking technologies; and chemical recycling technologies that would overcome some of the environmental and economic issues facing current technologies.

DEVELOP INSIGHTS AND BUILD AN ECONOMIC AND SCIENTIFIC EVIDENCE BASE. Many of the core aspects of plastic material flows and their economics are still poorly understood. While this report, together with a number of other recent efforts, aims to provide initial answers, more research is required. Initial studies could include: investigating in further detail the economic and environmental benefits of solutions discussed in this report; conducting meta-analyses and research targeted to assess the socio-economic impact of ocean plastics waste and substances of concern (including risks and externalities); determining the scale-up potential for greenhouse gas-based plastics (renewably sourced plastics produced using greenhouse gases as feedstock); investigating the potential role of (and boundary conditions for) energy recovery in a transition period; and managing and disseminating a repository of global data and best practices.

ENGAGE POLICYMAKERS in the development of a common vision of a more effective system, and provide them with relevant tools, data and insights related to plastics and plastic packaging. One specific deliverable could be a plastics toolkit for policymakers, giving them a structured methodology for assessing opportunities, barriers and policy options to overcome these barriers in transitioning towards the New Plastics Economy.

COORDINATE AND DRIVE COMMUNICATION of the nature of today's situation, the vision of the New Plastics Economy, best practices and insights, as well as specific opportunities and recommendations, to stakeholders acting along the global plastic packaging value chain.

PART I SUMMARY OF FINDINGS AND CONCLUSIONS

1 THE CASE FOR RETHINKING PLASTICS, STARTING WITH PACKAGING

Because of their combination of unrivalled properties and low cost, plastics are the workhorse material of the modern economy. Their use has increased twenty-fold in the past half-century, and is expected to double again in the next 20 years. Today nearly everyone, everywhere, every day comes into contact with plastics — especially plastic packaging, on which the report focuses.

While delivering many benefits, the current plastics economy has drawbacks that are becoming more apparent by the day. After a short first-use cycle, 95% of plastic packaging material value, or USD 80–120 billion annually, is lost to the economy. A staggering 32% of plastic packaging escapes collection systems, generating significant economic costs by reducing the productivity of vital natural systems such as the ocean and clogging urban infrastructure. The cost of such after-use externalities for plastic packaging, plus the cost associated with greenhouse gas emissions from its production, has been estimated conservatively by UNEP at USD 40 billion — exceeding the plastic packaging industry's profit pool. In future, these costs will have to be covered. In overcoming these drawbacks, an opportunity beckons: enhancing system effectiveness to achieve better economic and environmental outcomes while continuing to reap the many benefits of plastic packaging.

1.1 PLASTICS AND PLASTIC PACKAGING ARE AN INTEGRAL AND IMPORTANT PART OF THE GLOBAL ECONOMY

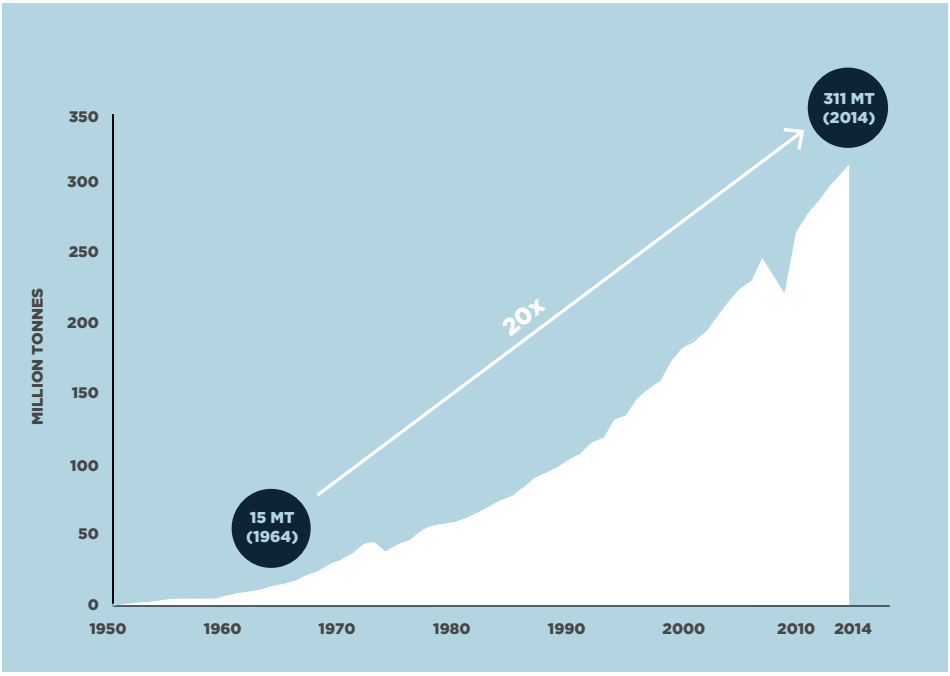
Today, imagining a world without plastics[1] is nearly impossible. Plastics are increasingly used across the economy, serving as a key enabler for sectors as diverse as packaging, construction, transportation, healthcare and electronics. Plastics now make up roughly 15% of a car[2] by weight and about 50% of the Boeing Dreamliner.[3]

Plastics have brought massive economic benefits to these sectors, thanks to their combination of low cost, versatility, durability and high strength-to-weight ratio.[4] The success of plastics is reflected in the exponential growth in their production over the past half-century (Figure 1). Since 1964, plastics production has increased twenty-fold, reaching 311 million tonnes in 2014, the equivalent of more than 900 Empire State Buildings.[5] Plastics production is expected to double again in 20 years and almost quadruple by 2050. Plastic packaging — the focus of this report — is plastics' largest application, representing 26% of the total volume.[6] As packaging materials, plastics are especially inexpensive, lightweight and high performing. Plastic packaging can also benefit the environment: its low weight reduces fuel consumption in transportation, and its barrier properties keep food fresh longer, reducing food waste. As a result of these characteristics, plastics are increasingly replacing other packaging materials.

Between 2000 and 2015, the share of plastic packaging as a share of global packaging volumes has increased from 17% to 25%[7] driven by a strong growth in the global plastic packaging market[8] of 5%[9] annually. In 2013, the industry put 78 million tonnes of plastic packaging on the market, with a total value of USD 260 billion.[10]

Plastic packaging volumes are expected to continue their strong growth, doubling within 15 years and more than quadrupling by 2050, to 318 million tonnes annually — more than the entire plastics industry today.[11] The main plastic resin types and their packaging applications are shown in Figure 2.

FIGURE 1: GROWTH IN GLOBAL PLASTICS PRODUCTION 1950–2014



Note: Production from virgin fossil-based feedstock only (does not include bio-based, greenhouse gas-based or recycled feedstock).

Source: PlasticsEurope, *Plastics – the Facts 2013* (2013); PlasticsEurope, *Plastics – the Facts 2015* (2015).

FIGURE 2: MAIN PLASTIC RESIN TYPES AND THEIR APPLICATIONS IN PACKAGING

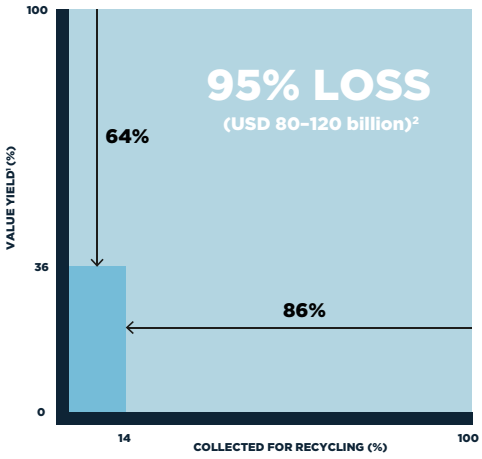
Source: Project MainStream analysis.

1.2 TODAY'S PLASTICS ECONOMY HAS IMPORTANT DRAWBACKS

1.2.1 Plastic packaging is an iconic linear application with USD 80–120 billion annual material value loss

Today, 95% of plastic packaging material value or USD 80–120 billion annually is lost to the economy after a short first use. More than 40 years after the launch of the well-known recycling symbol, only 14% of plastic packaging is collected for recycling. When additional value losses in sorting and reprocessing are factored in, only 5% of material value is retained for a subsequent use (see Figure 3). Plastics that do get recycled are mostly recycled into lower-value applications that are not again recyclable after use. The recycling rate for plastics in general is even lower than for plastic packaging, and both are far below the global recycling rates for paper (58%)[12] and iron and steel (70–90%).[13] PET,[14] used in beverage bottles, has a higher recycling rate than any other type of plastic, but even this success story is only a modest one: globally, close to half of PET is not collected for recycling, and only 7% is recycled bottle-to-bottle.[15] In addition, plastic packaging is almost exclusively single-use, especially in business-to-consumer applications.

FIGURE 3: PLASTIC PACKAGING MATERIAL VALUE LOSS AFTER ONE USE CYCLE



1 Value yield = volume yield * price yield, where volume yield = output volumes / input volumes, and price yield = USD per tonne of reprocessed material / USD per tonne of virgin material

2 Current situation based on 14% recycling rate, 72% volume yield and 50% price yield. Total volume of plastic packaging of 78 Mt, given a weighted average price of 1,100–1,600 USD/t

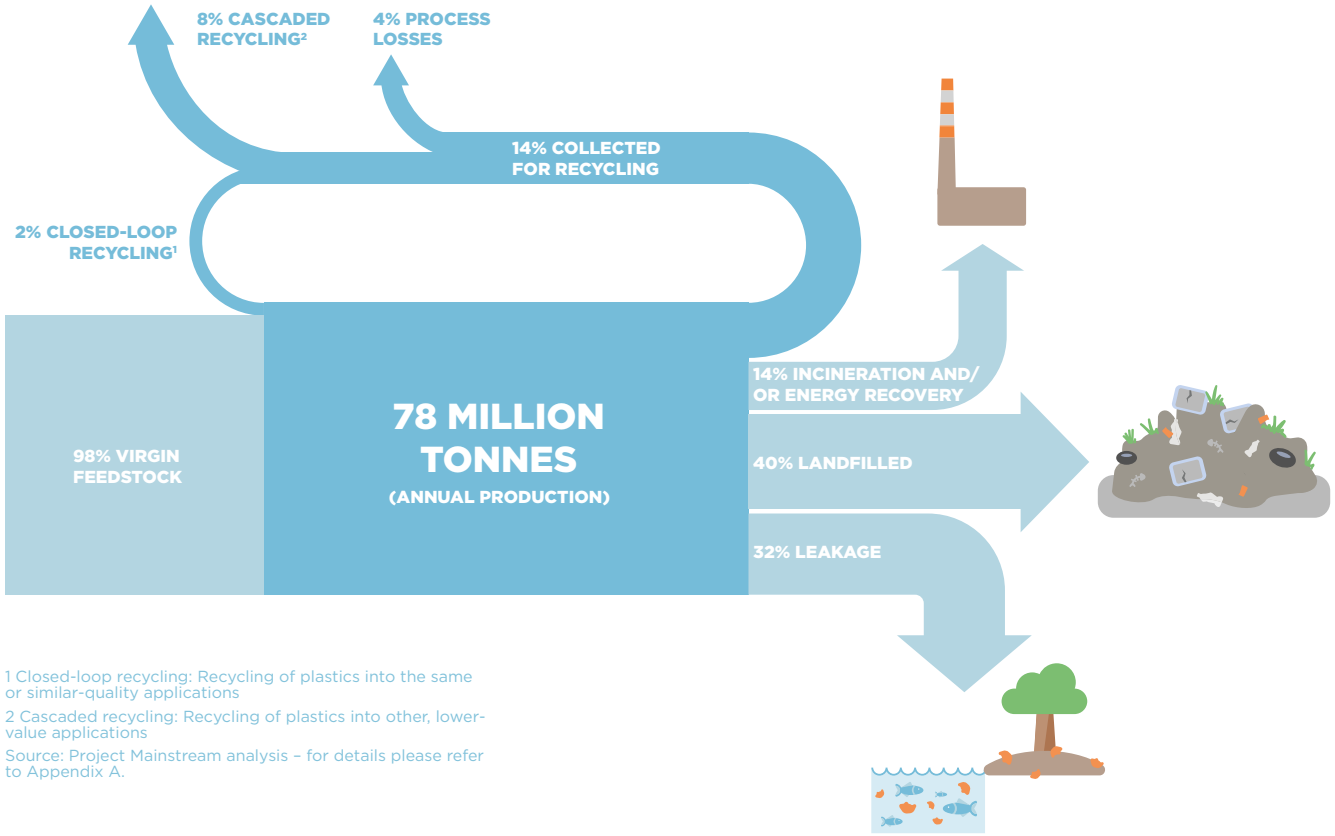
Source: Expert interviews; Plastic News; Deloitte, *Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment Final Report* (2015); The Plastics Exchange; plasticker; EUWID; Eurostat.

A comprehensive overview of global flows of plastic packaging materials can be found in Figure 4. In addition to the 14% of plastic packaging collected for recycling, another 14% is sent to an incineration and/or energy recovery process, mostly through incineration in mixed solid waste incinerators, but also through the combustion of refuse-derived fuel in industrial processes such as cement kilns, and (at a limited scale) pyrolysis or gasification. While recovering energy is a good thing in itself, this process still loses the embedded effort and labour that went into creating the material. For energy recovery in mixed solid waste incinerators, in particular, there are also concerns that over-deployment of such incineration infrastructure can create a 'lock-in' effect that, because of the large capital investments but relatively low operating costs involved in building up and running such infrastructure, can effectively push higher-value mechanisms such as recycling out of the market. Many organisations have also raised concerns about the pollutants that are generated during energy recovery processes, which can have direct negative health effects if adequate pollution controls are not in place, as is often the case in the developing world. Also, even if appropriate pollution controls are in place, the resulting by-products need to be disposed of.

Furthermore, an overwhelming 72% of plastic packaging is not recovered at all: 40% is landfilled, and 32% leaks out of the collection system — that is, either it is not collected at all, or it is collected but then illegally dumped or mismanaged.

This analysis of the global flows of plastic packaging materials is based on an aggregation of fragmented data sets, often with varying definitions and scope. The analysis not only reveals a significant opportunity to increase circularity and capture material value, but also highlights the need for better alignment of reporting standards and consolidation on a global level. Specific efforts could be dedicated to improving the data from developing markets with informal waste sectors.

FIGURE 4: GLOBAL FLOWS OF PLASTIC PACKAGING MATERIALS IN 2013



1 Closed-loop recycling: Recycling of plastics into the same or similar-quality applications

2 Cascaded recycling: Recycling of plastics into other, lower-value applications

Source: Project Mainstream analysis – for details please refer to Appendix A.

1.2.2 Production relies on finite stocks of fossil feedstocks

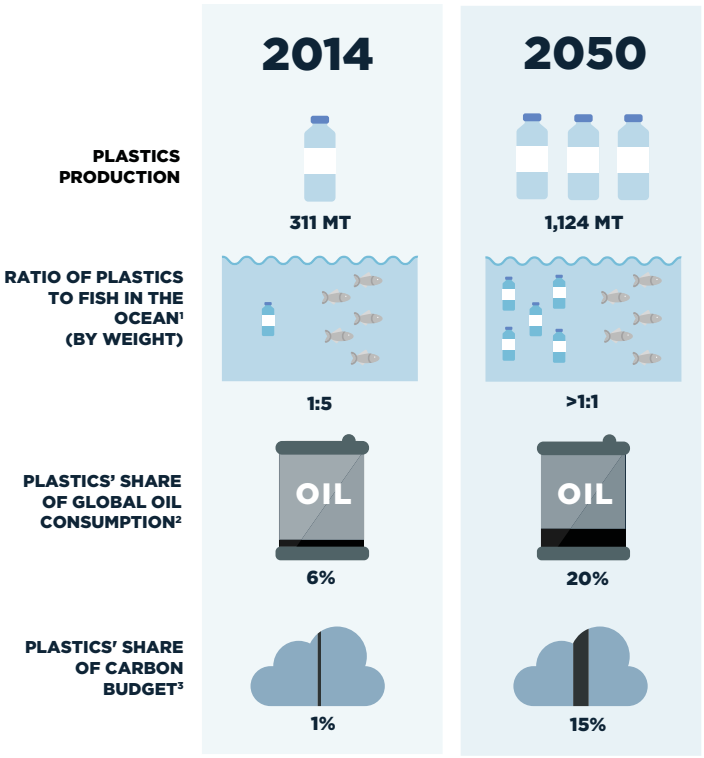
The plastics industry as a whole is highly reliant on finite stocks of oil and gas, which make up more than 90% of its feedstock. For plastic packaging, this number is even higher, as the recycling of plastics into packaging applications is limited. Sources vary on the share of oil production used to make plastics, but a combination of extensive literature research and modelling indicates that 4–8% of the world's oil production is used to make plastics (not just packaging), with 6% as the best estimate; roughly half of this is used as material feedstock and half as fuel for the production process.[16] This is equivalent to the oil consumption of the global aviation sector[17] and is in addition to the natural gas used as material feedstock and fuel. If the current strong growth of plastics usage continues as expected, the consumption of oil by the entire plastics sector will account for 20% of the total consumption by 2050.[18] The use of oil by the plastics industry is expected to increase in line with plastics production (growing by 3.5–3.8% annually); this is much faster than the growth in overall demand for oil, which is expected to increase by only 0.5% annually.[19]

1.2.3 Plastics and packaging generate significant negative externalities

The externalities related to the use of plastics and plastic packaging are concentrated in three areas: degradation of natural systems as a result of leakage, especially in the ocean; greenhouse gas emissions resulting from production and after-use incineration; and health and environmental impacts from substances of concern. *Valuing Plastic*, a report by UN Environment Programme and the Plastics Disclosure Project (PDP) based on research by Trucost estimated the total natural capital cost of plastics in the consumer goods industry at USD 75 billion, of which USD 40 billion was related to plastic packaging, exceeding the profit pool of the plastic packaging industry.[20]

The continued strong growth expected in the production and use of both plastics in general and plastic packaging in particular will spread the benefits of plastics to ever more people and in ever more useful applications; however, if production and use continue within the current linear framework, these negative externalities will be exacerbated, as laid out in Figure 5 and detailed below.

FIGURE 5: FORECAST OF PLASTICS VOLUME GROWTH, EXTERNALITIES AND OIL CONSUMPTION IN A BUSINESS-AS-USUAL SCENARIO



1 Fish stocks are assumed to be constant (conservative assumption)

2 Total oil consumption expected to grow slower (0.5% p.a.) than plastics production (3.8% until 2030 then 3.5% to 2050)

3 Carbon from plastics includes energy used in production and carbon released through incineration and/or energy recovery after-use. The latter is based on 14% incinerated and/or energy recovery in 2014 and 20% in 2050. Carbon budget based on 2 degrees scenario

Source: PlasticsEurope; ICIS Supply and Demand; IEA, *World Energy Outlook* (2015) (Global GDP projection 2013–2040 and Central 'New Policies' scenario oil demand projection 2014-2040, both assumed to continue to 2050); Ocean Conservancy and McKinsey Center for Business and Environment, *Stemming the Tide: Land-based strategies for a plastic-free ocean* (2015); J. R. Jambeck et al., *Plastic waste inputs from land into the ocean* (Science, 13 February 2015); J. Hopewell et al., *Plastics recycling: Challenges and opportunities* (Philosophical Transactions of the Royal Society B, 2009); IEA, CO_2 *emissions from fuel combustion* (2014); IEA, *World Energy Outlook Special Report: Energy and Climate Change* (2015); Carbon Tracker Initiative, *Unburnable Carbon* (2013).

Degradation of natural systems as a result of leakage, especially in the ocean. At least 8 million tonnes of plastics leak into the ocean each year[21] — which is equivalent to dumping the contents of one garbage truck into the ocean per minute. If no action is taken, this will increase to two per minute by 2030 and four per minute by 2050.[22] Estimates and expert interviews suggest that packaging represents the major share of the leakage. Not only is packaging the largest application of plastics with 26% of volumes, its small size and low residual value also makes it especially prone to leakage. One indicative data point is that plastic packaging comprises more than 62% of all items (including non-plastics) collected in international coastal clean-up operations.[23]

Plastics can remain in the ocean for hundreds of years in their original form and even longer in small particles, which means that the amount of plastic in the ocean cumulates over time. The best research currently available estimates that there are over 150 million tonnes of plastic waste in the ocean today.[24] Without significant action, there may be more plastic than fish in the ocean, by weight, by 2050.[25] Even by 2025, the ratio of plastic to fish in the ocean is expected to be one to three, as plastic stocks in the ocean are forecast to grow to 250 million tonnes in 2025.[26] As pointed out in the report *Stemming the Tide*, even if concerted abatement efforts were made to reduce the flow of plastics into the ocean, the volume of plastic waste going into the ocean would stabilise rather than decline, implying a continued increase in total ocean plastics volumes, unless those abatement efforts were coupled with a longer-term systemic solution, including the adoption of principles of the circular economy.

Ocean plastics significantly impact maritime natural capital. While the total economic impact is still unclear, initial studies suggest that it is at least in the billions of dollars. According to *Valuing Plastic* the annual damage of plastics to marine ecosystems is at least USD 13 billion per year and Asia-Pacific Economic Cooperation (APEC) estimates that the cost of ocean plastics to the tourism, fishing and shipping industries was USD 1.3 billion in that region alone.[27] Even in Europe, where leakage is relatively limited, potential costs for coastal and beach cleaning could reach EUR 630 million (USD 695 million) per year.[28] In addition to the direct economic costs, there are potential adverse impacts on human livelihoods and health, food chains and other essential economic and societal systems.

Leaked plastics can also degrade other natural systems, such as forests and waterways, and induce direct economic costs by clogging sewers and other urban infrastructure. The economic costs of these impacts need further assessment.

Greenhouse gas emissions. As pointed out above, plastic packaging can in many cases reduce the emission of greenhouse gases during its use phase. Yet, with 6% of global oil production devoted to the production of plastics (of which packaging represents a good quarter), considerable greenhouse gas emissions are associated with the production and sometimes the after-use pathway of plastics. In 2012, these emissions amounted to approximately 390 million tonnes of CO_2 for all plastics (not just packaging).[29] According to *Valuing Plastic*, the manufacturing of plastic feedstock, including the extraction of the raw materials, gives rise to greenhouse gas emissions with natural capital costs of USD 23 billion.[30] The production phase, which consumes around half of the fossil feedstocks flowing into the plastics sector, leads to most of these emissions.[31] The remaining carbon is captured in the plastic products themselves, and its release in the form of greenhouse gas emissions strongly depends on the products' after-use pathway.[32] Incineration and energy recovery result in a direct release of the carbon (not taking into account potential carbon savings by replacing another energy source). If the plastics are landfilled, this feedstock carbon could be considered sequestered. If it is leaked, carbon might be released into the atmosphere over many (potentially, hundreds of) years.[33]

This greenhouse gas footprint will become even more significant with the projected surge in consumption. If the current strong growth of plastics usage continues as expected, the emission of greenhouse gases by the global plastics sector will account for 15% of the global annual carbon budget by 2050, up from 1% today.[34] The carbon budget for the global economy is based on restricting global warming to a maximum increase of 2°C by 2100.[35] Even though plastics can bring real resource efficiency gains and help reduce carbon emissions during use, these figures show that it is crucial to address the greenhouse gas impact of plastics production and after-use treatment.

Substances of concern. Plastics are made from a polymer mixed with a complex blend of additives such as stabilisers, plasticisers and pigments, and might contain unintended substances in the form of impurities and contaminants. Substances such as bisphenol A (BPA) and certain phthalates, which are used as plasticisers in polyvinyl chloride (PVC), have already raised concerns about the risk of adverse effects on human health and the environment, concerns that have motivated some regulators and businesses to act.[36] In addition, there are uncertainties about the potential consequences of long-term exposure to other substances found in today's plastics, about their combined effects and about the consequences of leakage into the biosphere. The 150 million tonnes of plastics currently in the ocean include roughly 23 million tonnes of additives, of which some raise concern.[37] While the speed at which these additives leach out of the plastic into the environment is still subject to debate, estimates suggest that about 225,000 tonnes of such additives could be released into

the ocean annually. This number could increase to 1.2 million tonnes per year by 2050.[38] In addition, substances of concern might enter the environment when plastics and plastic packaging are combusted without proper controls, a common practice in many developing economies. This suggests the need for additional research and more transparency.

1.2.4 Current innovation and improvement efforts fail to have impact at scale

There are many innovation and improvement efforts that show potential, but to date these have proven to be too fragmented and uncoordinated to have impact at scale. Today's plastics economy is highly fragmented. The lack of standards and coordination across the value chain has allowed the proliferation of materials, formats, labelling, collection schemes, and sorting and reprocessing systems, which collectively hamper the development of effective markets. Innovation is also fragmented. The development and introduction of new packaging materials and formats across global supply and distribution chains is happening far faster than and is largely disconnected from the development and deployment of corresponding after-use systems and infrastructure. At the same time, hundreds, if not thousands, of small-scale local initiatives are being launched each year, focused on areas such as improving collection schemes and installing new sorting and reprocessing technologies. Other issues, such as the fragmented development and adoption of labelling standards, hinder public understanding and create confusion.

Through overcoming these drawbacks, an opportunity beckons: moving the plastics industry into a positive spiral of value capture, stronger economics, and better environmental outcomes. Actors across the plastic packaging value chain have proven time and again their capacity to innovate. Now, harnessing this capability to improve the circularity of plastic packaging — while continuing to expand its functionality and reduce its cost — could create a new engine to move towards a system that works: a New Plastics Economy.

2 THE NEW PLASTICS ECONOMY: CAPTURING THE OPPORTUNITY

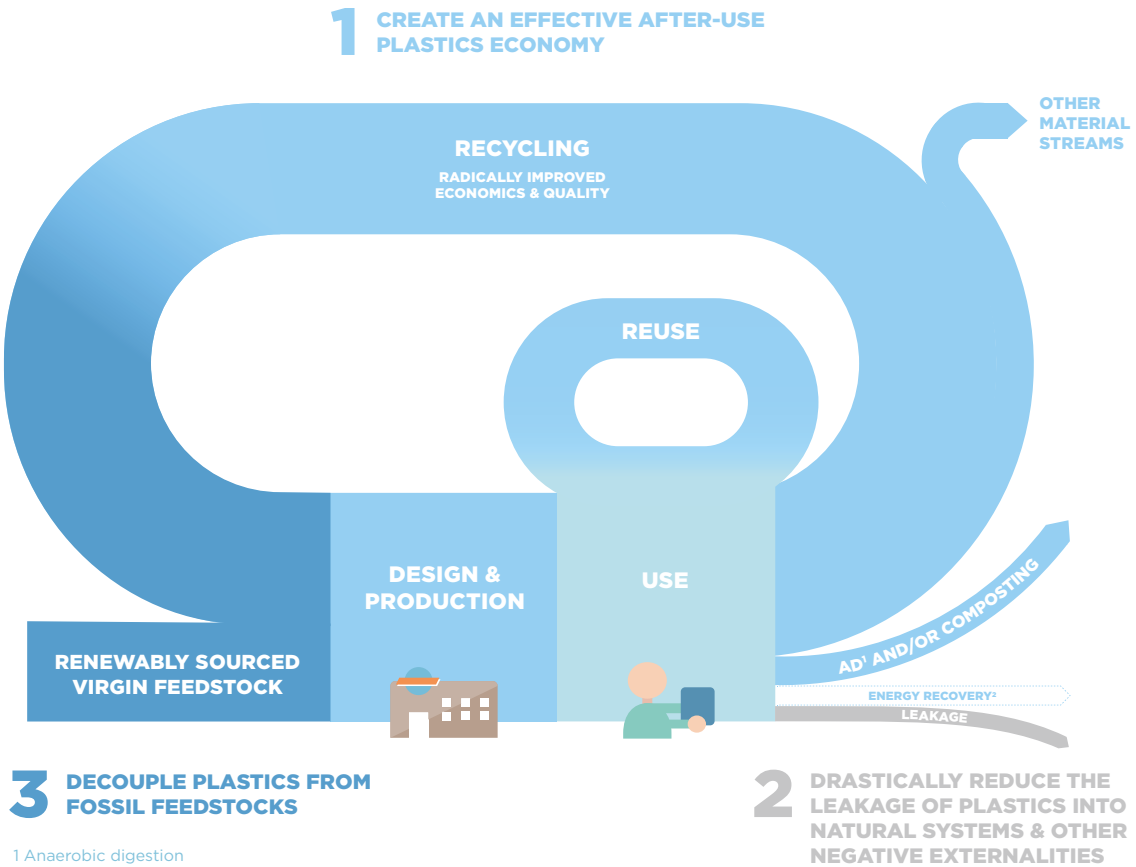
The overarching vision of the New Plastics Economy is that plastics never become waste; rather, they re-enter the economy as valuable technical or biological nutrients. The New Plastics Economy is underpinned by and aligns with circular economy principles. It sets the ambition to deliver better system-wide economic and environmental outcomes by creating an effective after-use plastics economy (the cornerstone and priority); by drastically reducing the leakage of plastics into natural systems (in particular the ocean); and by decoupling plastics from fossil feedstocks.

2.1 THE NEW PLASTICS ECONOMY PROPOSES A NEW WAY OF THINKING

The New Plastics Economy builds on and aligns with the principles of the circular economy, an industrial system that is restorative and regenerative by design (see Box 1). The New Plastics Economy has three main ambitions (see Figure 6):

1. **Create an effective after-use plastics economy by improving the economics and uptake of recycling, reuse and controlled biodegradation for targeted applications. This is the cornerstone of the New Plastics Economy and its first priority, and helps realise the two following ambitions.**
2. **Drastically reduce leakage of plastics into natural systems (in particular the ocean) and other negative externalities.**
3. **Decouple plastics from fossil feedstocks by — in addition to reducing cycle losses and dematerialising — exploring and adopting renewably sourced feedstocks.**

FIGURE 6: AMBITIONS OF THE NEW PLASTICS ECONOMY



1 Anaerobic digestion

2 The role of, and boundary conditions for, energy recovery in the New Plastics Economy need to be further investigated

Source: Project Mainstream analysis.

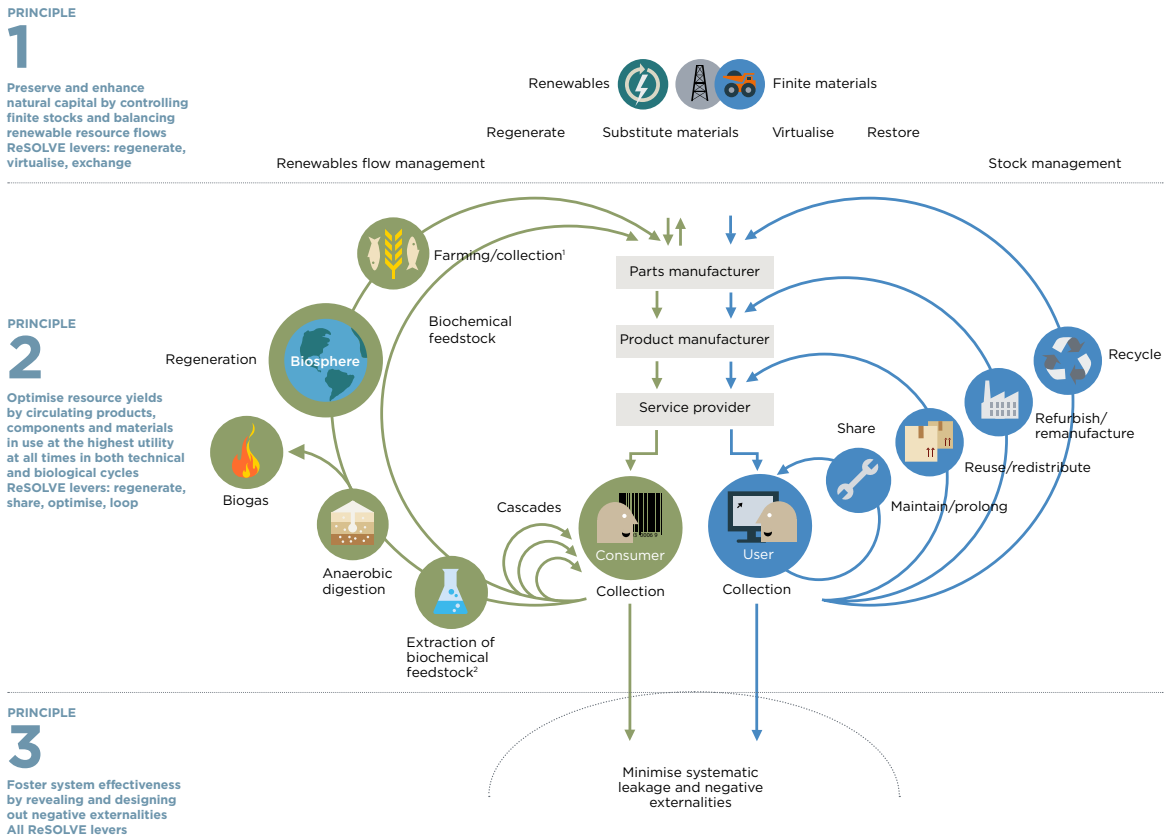
Even with today's designs, technologies and systems, these ambitions can already be at least partially realised. One recent study found, for example, that in Europe already today 53% of plastic packaging could be recycled 'eco-efficiently'.[39] While the exact figure can be debated and depends on, amongst others, the oil price, the message is clear: there are pockets of opportunities to be captured today — and even where not entirely feasible today, the New Plastics Economy offers an attractive target state for the global value chain and governments to collaboratively innovate towards. This will not happen overnight. Redesigning materials, formats and systems, developing new technologies and evolving global value chains may take many years. But this should not discourage stakeholders or lead to delays — on the contrary, the time to act is now.

Box 1: The circular economy: Principles and benefits

The circular economy is an industrial system that is restorative and regenerative by design. It rests on three main principles: preserving and enhancing natural capital, optimising resource yields, and fostering system effectiveness (see Figure 7).

Multiple research efforts and the identification of best-practice examples have shown that a transition towards the circular economy can bring about the lasting benefits of a more innovative, resilient, and productive economy. For example, the 2015 study *Growth Within: A Circular Economy Vision for a Competitive Europe* estimated that a shift to the circular economy development path in just three core areas — mobility, food and built environment — would generate annual total benefits for Europe of around EUR 1.8 trillion (USD 2.0 trillion).[40]

FIGURE 7: OUTLINE OF A CIRCULAR ECONOMY



1 Hunting and fishing

2 Can take both post-harvest and post-consumer waste as an input

Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

Given plastic packaging's many benefits, it has become clear that the likelihood of a drastic reduction in the volume of plastic packaging is low — although reduction should be pursued where possible and beneficial, by moving away from single-use as the default (especially in business-to-business applications, but also in targeted business-

to-consumer applications such as plastic bags), by dematerialising and by substituting other materials.

2.1.1 Create an effective after-use plastics economy

Creating an effective after-use plastics economy is the cornerstone of the New Plastics Economy and its first priority. Not only is it critical to capture more material value and increase resource productivity, it also provides a direct economic incentive to avoid leakage into natural systems and helps enable the transition to renewably sourced feedstock by reducing its scale.

As evidenced by today's capture of just 5% of after-use plastic packaging material value, there is significant potential to capture more material value by radically improving recycling economics, quality and uptake. Coordinated and compounding action and innovation across the global value chain are needed to capture the potential. These actions could include: establishment of a cross-value chain dialogue mechanism; development of a Global Plastics Protocol to set direction on the redesign and convergence of materials, formats, and after-use systems to substantially improve collection, sorting and reprocessing yields, quality and economics, while allowing for regional differences and continued innovation; enablement of secondary markets for recycled materials through the introduction and scale-up of matchmaking mechanisms, industry commitments and/or policy interventions; pursuit of innovation opportunities that have the potential to scale up, such as investments in new or improved materials and reprocessing technologies; and exploration of the enabling role of policy. Segments within the plastic packaging market with the most attractive recycling cost-benefit balance are likely commercial (business-to-business) films, beverage bottles and other rigid plastic packaging.[41]

Reuse could play an important role as well, especially in the business-to-business (B2B) segment. Reusable B2B packaging can create substantial cost savings, and if used in pooled systems across companies and industries, significant value beyond packaging. In its most advanced form, it could help enable the 'Physical Internet' — a logistics system based on standardised, modularised, shared assets. Transitioning to the 'Physical Internet' could unlock significant economic value — estimated to be USD 100 billion and a 33% reduction in CO_2 emissions annually in the United States alone.[42] In the business-to-consumer segment, reuse is more challenging for many applications, but could however be pursued for targeted applications such as plastic bags, and could be increasingly enabled by new business models.

Industrially compostable plastic packaging could be a good solution and scaled up for certain targeted applications, if coupled with the appropriate collection and recovery infrastructure (anaerobic digestion and/or industrial composting) to return the nutrients of the packaged contents (e.g. food) to the soil. Today, plastics are designed to be either recyclable or compostable (or neither of the two) — keeping both options open by design is usually not possible with current materials technology and after-use infrastructure. For most applications, the recycling pathway is preferable, as this keeps the material in the economy, whereas biodegradability allows plastic to break down into harmless, but essentially low-value elements such as water and CO_2. In certain targeted applications, however, industrially compostable packaging could be a valuable mechanism for returning nutrients to the soil. Most promising applications are the ones that meet the following two criteria. First, packaging is likely to be mixed with organic contents such as food after use — making packaging in such applications compostable can help to bring back nutrients from the packaged contents (e.g. food) to the soil. Second, packaging does not typically end up in a plastics recycling stream — compostable packaging in its current form can interfere with recycling processes. Examples of applications fulfilling both criteria are bags for organic waste, packaging used in closed-loop systems such as events, fast food restaurants and canteens, and packaging items such as teabags and coffee capsules. The city of Milan, for example, more than tripled its collection of food waste — from 28kg to 95kg per inhabitant per year — after the introduction of compostable bags for organic waste.[43]

2.1.2 Drastically reduce the leakage of plastics into natural systems and other negative externalities

Plastics should not end up in the ocean or other parts of the environment. Ensuring this doesn't happen requires a coordinated effort to improve collection systems and recovery infrastructure — especially where the latter lags behind economic development, as is the case for many rapidly developing middle-income countries in Asia, which account for an estimated 80% of leakage. Various local and global initiatives address the critical development of infrastructure and work with the formal and informal waste management sector to stop plastics from leaking into the ocean. Local initiatives include, for example, the Mother Earth Foundation and Coastal Cleanup in the Philippines, while the Trash Free Seas Alliance, initiated by the Ocean Conservancy, is an example of an effort aimed at effecting change on a global scale.

But even a concerted effort to improve collection and recovery infrastructure in high-leakage countries would likely only stabilise the flow of plastics into the ocean — not stop it — which means that the total volume of plastics in the ocean would continue to increase, given the cumulative nature of ocean plastics.[44] As argued by the Ocean

Conservancy in *Stemming the Tide* and by many others, a long-term root-cause solution would include the incorporation of circular economy principles into the plastics sector. Creating a working economy for after-use plastics would offer a direct economic incentive to build collection and recovery infrastructure. Furthermore, because plastics with high after-use value are less likely to leak, especially in countries with an informal waste sector, improving the design of products and materials to enhance after-use value would reduce leakage. Finally, levers such as reuse and dematerialisation can be a means of reducing the amount of plastic put on the market and, hence, reducing leakage proportionally.

Even with all these efforts, leakage is likely to remain significant. Even in the United States and Europe, with advanced collection systems, 170,000 tonnes of plastics leak into the ocean each year.[45] Therefore, efforts to avoid leakage into the ocean would require complementary innovation efforts to make plastic packaging 'bio-benign' when it does (unintentionally) leak into the environment. Today's biodegradable plastics do not measure up against such an ambition, as they are typically compostable only under controlled conditions, as in industrial composters. Nor has additive-mediated fragmentation (for example, oxo-fragmentation) led to a breakthrough — such plastics have not been proven truly benign, but rather mostly led to fragmentation, hence increasing the amount of microplastics in the ocean.

Hence, game-changing innovation is needed to make plastics truly bio-benign in case they leak outside collection systems. Different avenues might help to reduce the harm of (unintentionally) leaked plastics: advanced biodegradability in freshwater and/or marine environments, a material palette without substances of concern, avoidance of colours and shapes that are typically ingested or otherwise harmful to marine life for applications with high risks of leakage, and radically new smart/triggered processes that imitate metabolising processes in nature could all contribute to making materials benign to natural systems. Paper offers inspiration — a widely used and recyclable packaging material that is relatively benign if leaked into the environment (unless it contains substances of concern, such as certain inks). Developing such bio-benign materials that are still recyclable and competitive in terms of functionality and costs demands further research of what constitutes bio-benign and represents a significant innovation challenge that will take time to overcome.

While scientific evidence on the exact implications of substances of concern is not always conclusive, especially due to the difficulty of assessing complex long-term exposure and compounding effects, there are sufficient indications that warrant further research into, and accelerated development and application of, safe alternatives. These research and innovation efforts would need to be complemented with enhanced transparency on material content of plastics and, where relevant, the application of the precautionary principle to possibly phase out specific (sets of) substances raising concerns of acute negative effects.

2.1.3 Decouple plastics from fossil feedstocks

Recycling and reuse are critical to decoupling plastic packaging use from the consumption of fossil-based feedstock. However by themselves they are probably insufficient. Even if global recycling rates rose from today's 14% to more than 55% — which would be higher than the rate achieved today by even the best-performing countries — annual requirements for virgin feedstock would still double by 2050.[46]

The likely remaining, albeit diminishing, cycle losses from reuse and recycling loops and the attendant need for virgin feedstock to compensate for those losses call for exploring the role of renewable sources — either directly converting greenhouse gases like methane and carbon dioxide (GHG-based sources) or using biomass (bio-based sources). Innovators claim that production of GHG-based plastics is already cost competitive to current fossil-based plastics for certain applications and qualify as carbon negative materials.[47] Using bio-based sources without creating significant externalities in other domains requires applying regenerative agricultural principles and taking the impacts of the agricultural processes, including land use and bio-diversity, into account.

Box 2: The role of Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle.[48] As such, if implemented well, it can provide a valuable tool to evaluate different options at any given point in time. Like any tool, however, it has its limitations. Most fundamentally, while it is well suited to evaluate individual choices today, it is less suitable for determining the target state towards which a system as a whole could innovate. Also, similar to the prisoner's dilemma, the classic example from game theory in which the individual maximisation of benefits by rational actors leads to a suboptimal overall outcome, an LCA optimisation by each individual actor does not necessarily lead to better system outcomes.

Take the case of electric vehicles. Most people would agree that a mobility system supported by electric, grid-integrated vehicles and renewable electricity is a more attractive target state than one reliant on

combustion engines and fossil fuels. However, an LCA study published in 2011 found that the carbon advantage of an electric vehicle over a similar conventional petrol car could be as small as 4%, and that 'drivers wanting to minimise emissions could be better off buying a small, efficient petrol or diesel car'.[49] The right conclusion is clearly not to write off the concept of electric vehicles. Rather, a good conclusion might be to acknowledge both the inherent attractiveness of the electric vehicle target state while also acknowledging the innovation opportunity and need to develop better-performing electric vehicles, improve effectiveness and efficiency of production processes and after-use management, and increase the uptake of renewable sources of electricity.

Similar reasoning can be applied to many of the mechanisms described in the vision for the New Plastics Economy. An economy in which the value of products and materials is maximised through multiple loops could be considered inherently more attractive than an economy with one-way linear material flows where 95% of material value is lost after one use cycle. Similarly, an economy in which plastics are sourced renewably from greenhouse gases or biomass coupled with the application of regenerative agricultural principles, could be considered inherently more attractive than an economy in which plastics are sourced from finite stocks of greenhouse gas-emitting fossil feedstocks. That preference does not necessarily imply that every piece of plastic packaging should be recycled or renewably sourced today, but it does offer a target state for the plastic packaging value chain to innovate towards.

Finally, the life cycle assessments in recent publications on plastic packaging tend to focus on single measures, such as carbon. While such measures are of the utmost importance, a single-measure focus inevitably fails to consider the entire impact of plastic across the life cycle, including the effects of leakage into the natural environment.

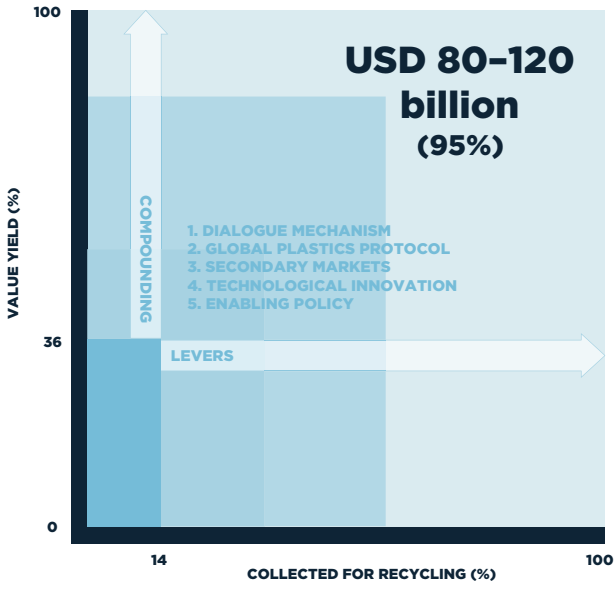
2.2 THE NEW PLASTICS ECONOMY COULD BRING SUBSTANTIAL BENEFITS

The New Plastics Economy aims to create long-term systemic value by fostering a working after-use economy, drastically reducing leakage and decoupling plastics from fossil feedstocks.

A business-as-usual scenario for plastics will also bring growth, innovation and benefits, but if circular economy principles guide and inspire this growth and innovation, the sum of the benefits will be larger. In particular, the New Plastics Economy provides several expected additional benefits, the most significant of which are capturing material value and de-risking the value chain by reducing negative externalities. The ambitions described in this report, such as increasing the economics and uptake of recycling and developing renewably sourced plastics, will help in the seizing of those opportunities.

The New Plastics Economy could help capture plastic packaging material value. Currently just 5% of material value of plastic packaging is captured after one use cycle, corresponding to USD 4–6 billion.[50] While it is unlikely that the industry could seize the full potential of material value, concerted action on redesigning and converging on materials, formats and after-use systems through a global plastics protocol, enablement of secondary markets and innovating on technology and materials could allow to capture a significant share (see Figure 8).

FIGURE 8: THEORETICAL POTENTIAL TO CAPTURE MATERIAL VALUE



Source: Project MainStream analysis.

Working towards the New Plastics Economy would significantly reduce the negative externalities associated with plastics and plastic packaging. As explained above, the benefits of plastic packaging are accompanied by substantial and accumulative degradation of natural systems due, in particular, to leakage into the ocean and to greenhouse gas emissions. Through creating effective after-use markets, the New Plastics Economy provides a direct incentive to build up collection and reprocessing infrastructure, and hence reduce leakage. Through increased reuse and recycling and by developing renewably sourced plastic materials, the New Plastics Economy actively mitigates the risk related to greenhouse gas emissions. Recycling one additional tonne of plastics, for example, reduces emissions by 1.1–3.0 tonnes of CO_2e compared to producing the same tonne of plastics from virgin fossil feedstock.[51] Some bio-based plastics also have been shown to have a negative global warming potential with -2.2 kilogram CO_2e per kilogram of bio-based PE produced compared to 1.8 kilogram CO_2e per kilogram of fossil-based PE produced.[52] By promoting more research on potential adverse effects, increasing transparency on material content and developing plastics without substances of concern, the New Plastics Economy helps mitigate risks posed by substances of concern.

Reducing these negative externalities would result in real risk-reduction benefits for businesses. While externalities by definition do not represent a direct cost to businesses, they expose businesses to regulatory risks, including the internalisation of negative externalities and even banning the use of specific types of plastic packaging, with potentially large impacts on the plastic packaging industry. The carbon tax — a tax levied on the carbon content of fuels, aimed at reducing greenhouse gas emissions — provides an example of risk internalisation. The possibility of an outright ban arose in India in 2015 when the National Green Tribunal considered imposing a ban on the use of plastics for packaging of all non-essential items, including multilayer packaging and PET bottles.[53] In addition, risks can also manifest themselves through customers — for example, bottle company SIGG USA went bankrupt in 2011 following a scandal about some of its products allegedly leaching the controversial substance bisphenol A.[54]

The New Plastics Economy can help reduce exposure to volatility of (fossil-based) virgin feedstock. Since the turn of the century, oil prices have been subject to very significant volatility. Although prices have dropped from the historical high seen in 2008 and are expected by some observers not to rise again soon, historically observed volatility could remain. The magazine 'The Economist' predicted in March 1999 that oil prices, then at USD 10 per barrel, would likely drop to USD 5.[55] By the end of that year they were at USD 25. Less than 10 years later they were at USD 145. Most major forecasters at the end of the 1990s agreed that oil prices would likely stay below USD 30 for the next two decades[56] — again proven wrong by the events of the next decade. The unpredictable cost of supply for fossil feedstock-based plastics is a risk, and one option for businesses wanting to address their exposure to that risk could be diversification into recycled and renewably sourced alternatives. Of course, these renewably sourced plastics are also derived from commodity feedstocks with market prices subject to local market pressures, so price volatility is still a concern, but diversification spreads the risks. Investments aimed at broadening the array of options for recycled materials and renewably sourced feedstocks would further help to build in system resilience in the New Plastics Economy.

2.3 NOW IS AN OPPORTUNE MOMENT TO ACT

A favourable alignment of factors makes now an opportune moment to act. New technologies are unlocking new opportunities, while the building up of after-use infrastructure in developing countries has made this a critical crossroads moment for getting systems right the first time. Concurrently, increasing regulatory action and growing societal concerns are morphing from a marginal to an increasingly central issue, potentially affecting companies' licence to operate.

New technologies are unlocking new opportunities in areas such as material design, separation technology, reprocessing technology and renewably sourced and biodegradable plastics. Dow Chemical recently developed, together with Printpack and Tyson Foods and for a specific set of applications, a mono-material stand-up pouch with improved recyclability versus the existing multi-material alternatives.[57] Chemical marker systems are advancing: the European Union's Polymark project, for example, is developing a system to reliably detect and sort food-contact PET.[58] WRAP is working on machine-readable fluorescent inks and sorting technologies to improve polymer identification.[59] The adoption of reprocessing technologies such as depolymerisation has been limited due to economics, but in the Netherlands Ioniqa Technologies has developed a cost-competitive process for PET that takes place at relatively low operating temperatures.[60] The production of plastics from captured greenhouse gases has been piloted and is claimed to be cost competitive. For example, Newlight's AirCarbon technology can convert methane to PHA, or carbon dioxide to polyurethane and thermoplastics.

Many developing countries are building up after-use infrastructure, making this a critical crossroads moment. Investments made now will determine the

infrastructure for the coming decades. Coordinating action and agendas across the value chain could catalyse impact.

A growing number of governments have implemented — or are considering implementing — policies related to plastic packaging. In Europe, the European Commission's recently adopted Circular Economy package includes the action to develop a strategy on plastics in the circular economy, a target to increase plastic packaging recycling to 55%, a binding target to reduce landfill to 10% of all waste by 2030, and a total ban on landfilling of all separately collected waste.[61] With the exception of Iceland, all of the Nordic countries operate container deposit schemes. Such schemes have also been deployed in the United States, where the overall recycling rate is 34%[62] while states with container deposit laws have an average rate of 70%; Michigan's USD 0.10 deposit is the highest in the nation, as is its recycling rate of 95% in 2013.[63] In 2015, a European Union directive came into force that required member states to reduce the use of plastic carrier bags.[64] France, for example, will outlaw single-use plastic bags as of January 2016.

Other countries have acted to restrict the use of plastic bags and other plastic packaging formats because of their impact on the local environment: In 2002, Bangladesh became the first country to ban plastic bags, after they were found to have choked drainage systems during devastating floods.[65] Rwanda followed suit in 2008[66]; and so did China, also in 2008, reducing the number of plastic bags in circulation by an estimated 40 billion in just one year.[67] All in all, more than 25 countries around the globe either ban or tax single-use plastic bags, and restrictions on the use of other highly littered packaging formats are being discussed. Guyana has announced plans to ban the import and use of expanded polystyrene (EPS, commonly known under one of its brand names, Styrofoam) from January 2016; EPS has been widely adopted as single-use food service packaging and makes up 2–5% of Guyana's waste stream.[68]

The United States has seen activity at city, state and federal levels. In 2014, Washington DC banned the use of food service products made of expanded polystyrene, joining the ranks of tens of other US cities.[69] In 2015, San Francisco took a step towards its 2020 goal of zero waste by banning the sale of plastic bottles in all public places.[70] At state level, 70 laws were enacted between 1991 and 2011 to establish extended producer responsibility (EPR) programmes: 40 of these came in the three years up to 2011.[71] These laws currently cover products like batteries, carpets and cell phones, not packaging, but they show state governments taking action to internalise the costs of dealing with negative externalities.[72] State activity can also be a precursor to federal action; in December 2015, after legislation had been passed in nine states, the House of Representatives voted to ban the use of synthetic microplastics in personal care products. If enacted into federal law, the legislation would supersede all state bans.[73] While this is not a packaging example, it is indicative of broader policy action in the plastics industry.

Society's perception of plastics is deteriorating and perhaps threatening the plastics industry's licence to operate. According to PlasticsEurope, an industry organisation, 'There is an increasingly negative perception of plastics in relation to health, environment and other issues'.[74] Issues such as ocean plastics are increasingly capturing the attention of individuals and policymakers.

2.4 WHERE TO START

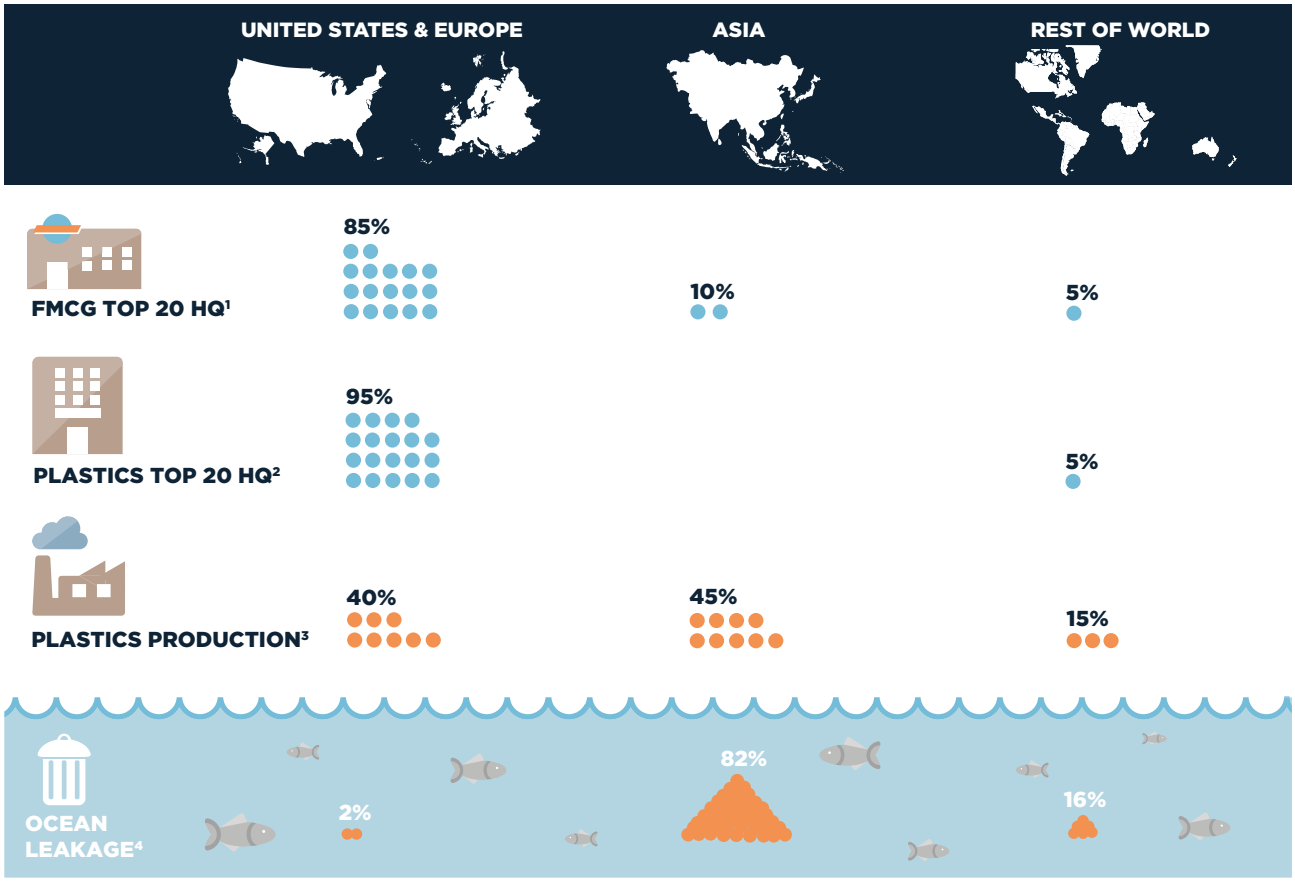
The United States, Europe and Asia jointly account for 85% of plastics production, roughly split equally between the United States and Europe on the one hand and Asia on the other (see Figure 9). Both regions are critical in the shift towards the New Plastics Economy and would be good places to start.

Given that Asia accounts for more than 80% of the total leakage of plastic into the ocean — at least according to the best available data[75] — this region has been the focus for a variety of crucial leakage mitigation efforts aimed at improving basic collection infrastructure.

Europe and the United States are home not only to significant shares of the production of plastic packaging, but also to the overwhelming majority of the top global companies relevant to the global plastic packaging industry, including the key global decision-makers at the start of the plastic packaging value chain — those who determine design (see Figure 9). Many of the opportunities around product and material redesign and around innovation in advanced technologies in separation and reprocessing can be found in these regions.

This report intends to pay special attention to innovation and redesign, a topic less explored in other work. As a consequence the focus is mainly on Europe and the United States. The report aims nevertheless to be relevant globally, at the same time acknowledging that other regions, especially in the developing world, will have different challenges, including putting basic collection and recovery infrastructure in place, leapfrogging to higher-performing after-use systems (i.e. first time right) based on expected evolutions, and working with the informal waste collection sector, including a focus on workers' health and safety.

FIGURE 9: DISTRIBUTION OF PLASTICS HEADQUARTERS, PRODUCTION, AND LEAKAGE



1 Headquarters of the global top 20 FMCG (Fast Moving Consumer Goods) companies (measured by 2014 global net sales)

2 Headquarters of the top 20 plastics and resin manufacturers (measured by 2015 global capacity)

3 Production of plastics material volumes (excluding thermoplastics and polyurethanes)

4 Source of plastics leaked into the oceans (proportion of the total global leakage measured in million tonnes of plastic marine debris leaked per year)

Source: PlasticsEurope, *Plastics – the Facts 2015* (2015); Statista; ICIS Supply and Demand; J. R. Jambeck et al., *Plastic waste inputs from land into the ocean* (Science, 13 February 2015).

3 THE NEW PLASTICS ECONOMY DEMANDS A NEW APPROACH

To move beyond small-scale and incremental improvements and achieve a systemic shift towards the New Plastics Economy, existing improvement initiatives would need to be complemented and guided by a concerted, global collaboration initiative that matches the scale of the challenge and the opportunity. Such an initiative does not exist today, and therefore would need to be set up, driven by an independent coordinating vehicle.

The aim of such a vehicle would be to stimulate development of a circular economy approach to plastics and plastic packaging as an integral part of the future economy. It would also aim for positive broader economic impacts and — directly or indirectly — to the protection and restoration of natural systems.

At the heart of the vehicle's design and set-up would be the recognition that innovation for and transition to the New Plastics Economy must be driven by joint, urgent, collaborative initiatives across industries, governments and NGOs. This would make it possible to address the chronic fragmentation and the lack of global standards, to benefit the development of effective markets. In such an initiative, consumer goods companies, plastic packaging producers and plastics manufacturers would play a critical role as they define the products and materials that are put on the market. Cities control the after-use infrastructure in many places, and are often hubs for innovation. Businesses involved in collection, sorting and reprocessing are an equally critical part of the puzzle. Policymakers can play an important role in enabling the transition by realigning incentives, facilitating secondary markets, defining standards and stimulating innovation. NGOs can help ensure that broader social and environmental considerations are taken into account. Collaboration would be required to overcome fragmentation, the chronic lack of alignment between innovation in the design and after-use stages, and the lack of standards — challenges that must be resolved in order to unlock the opportunities of the New Plastics Economy.

This vehicle would need to bring together the different actors in a cross-value chain dialogue mechanism and drive change by focusing on efforts with compounding effects that together would have the potential to shift the global market. Analysis to date suggests that the initial areas of focus could be:

1. **ESTABLISH THE GLOBAL PLASTICS PROTOCOL AND COORDINATE LARGE-SCALE PILOTS AND DEMONSTRATION PROJECTS.**
2. **MOBILISE LARGE-SCALE, TARGETED 'MOON SHOT' INNOVATIONS.**
3. **DEVELOP INSIGHTS AND BUILD A BASE OF ECONOMIC AND SCIENTIFIC EVIDENCE.**
4. **ENGAGE POLICYMAKERS.**
5. **COORDINATE AND DRIVE COMMUNICATION.**

ESTABLISH THE GLOBAL PLASTICS PROTOCOL AND COORDINATE LARGE-SCALE PILOTS AND DEMONSTRATION PROJECTS

Flying around the world without international air traffic control standards and surfing the web without global IP standards would be impossible. While globally adopted standards and protocols can be found in other complex industries, today's plastic packaging value chain lacks such alignment. A global plastics protocol would be needed to provide a core set of standards as the basis on which to innovate. It could provide guidance on design, labelling, marking, infrastructure and secondary markets, allowing for regional differences and innovation, in order to overcome the existing fragmentation and to fundamentally shift after-use collection and reprocessing economics and market effectiveness.

The Global Plastics Protocol would aim to redesign and converge materials, formats and after-use systems.

It would investigate questions such as:

To what extent could plastic packaging be designed with a significantly smaller set of material/additive combinations, and what would be the resulting economic benefits? What would be the potential of designing out small-format/low-value plastic packaging such as tear-offs with challenging after-use economics and a high likelihood of leakage? What would be the economic benefits of harmonising labelling and chemical marking across plastic packaging and aligning it with after-use separation and sorting systems? What if after-use systems, currently largely fragmented across municipalities due to uncoordinated historic developments, were rethought and redesigned to achieve optimal scale and economics? What would be the best levers to stimulate the market for recycled plastics?

The Global Plastics Protocol would set global direction by answering such questions, demonstrate solutions at scale with large-scale pilots and

demonstration projects, and drive global convergence (allowing for continued innovation and regional variations) towards the identified designs and systems with proven economics.

Involving players from across the global value chain in a dialogue mechanism, the protocol would, for example, build on the following elements:

Set up a global, industry-wide, ongoing effort to develop and facilitate adoption of globally recognised plastic packaging design standards. This effort could leverage existing work on design guidelines from organisations such as RECOUP, WRAP, ARP, EPBP and EUPR, and The Consumer Goods Forum,[76] but also go beyond to investigate and promote fundamental redesign and convergence of materials and formats. By aligning actors along the value chain — such as plastics and packaging producers, brand owners, retailers and after-use collection and reprocessing companies — such standards could fundamentally improve the circularity of material flows.

Converge towards clearly defined global labelling and material marking standards that are aligned with sorting and separation systems and that facilitate the sorting of plastics after use into high-value resource streams.

Redesign and converge towards a set of clearly defined collection and sorting archetypes, allowing for continued innovation and regional variation. The fragmentation of current collection and sorting systems comes with several disadvantages: fragmented after-use systems cannot be aligned with the design stage (most packaging is designed and produced at international scale and cannot be tailored to individual municipalities); citizens are confused about how plastics should be disposed of; and system-wide optimisation and economies of scale are lacking. While socio-economic differences need to be accounted for to some extent, there is ample room for systems redesign and convergence towards a set of archetypes. Redesigning systems and converging towards such well-defined archetypes within the Global Plastics Protocol would allow alignment across the value chain. Material and packaging design, for example, could be optimised for clearly specified sorting facilities and consistent labelling harmonised across regions. This effort would be complementary to multiple local and global efforts that are focused on building up collection and sorting infrastructure. It would inform those efforts at a critical point in their development and avoid getting locked into suboptimal infrastructure.

Establish a global framework for the implementation of modular and reusable business-to-business (B2B) packaging, building on the Physical Internet — a new logistics paradigm enabling a new era of modular, reusable B2B packaging. The convergence of fragmented activities towards such a framework on a global scale could significantly improve asset utilisation and global material flows.

Scale up the use of industrially compostable plastics for targeted applications, returning nutrients from the organic contents (such as food) of the packaging to the soil. This needs to be coupled with adequate infrastructure, as demonstrated successfully, for example, in the city of Milan and at the London Olympics.

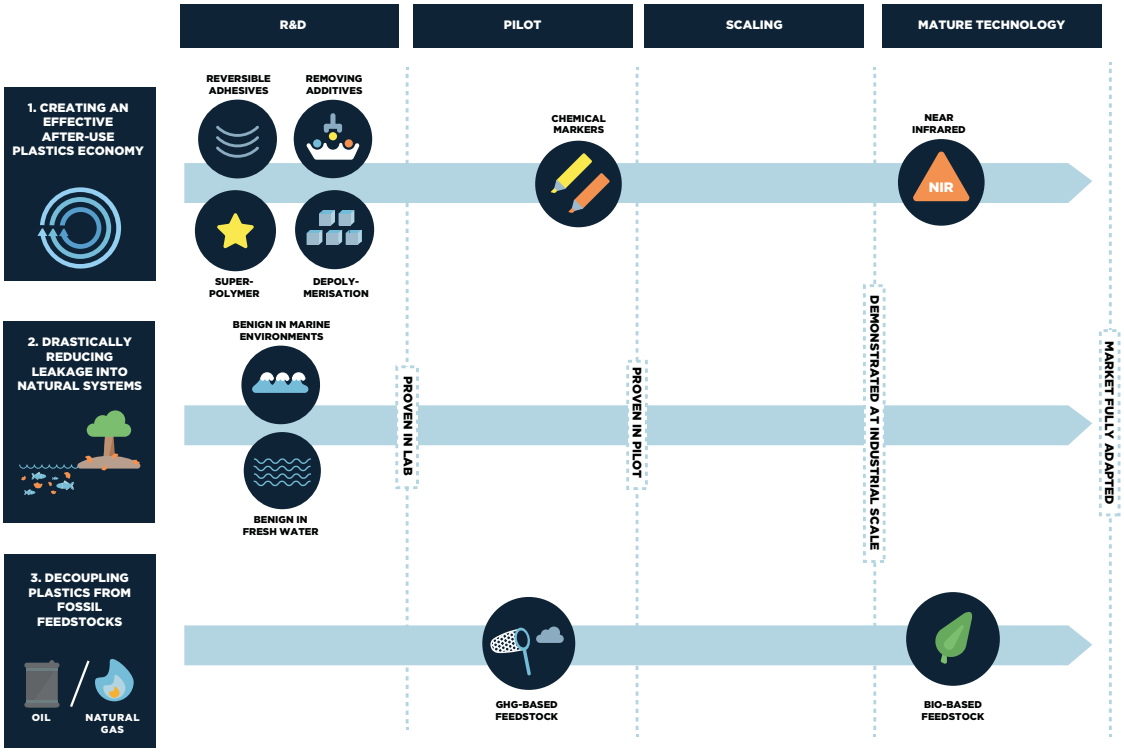
Transform and strengthen markets for recycled plastics, for example, by introducing and scaling up matchmaking mechanisms, for example using aggregator software or platforms to include companies not yet participating on both sides of the recycled plastics market — that is, smaller reprocessing companies and companies that source recycled content at the small- to medium scale; by allowing for more granular and standardised material specifications and better matching of supply and demand; and by strengthening demand for recycled content through industry commitments and/or policy.

Demonstrate the viability of high-value cascaded recycling by establishing cascaded flows of recycled plastics with a selected group of companies using the same material. This could include both packaging and non-packaging companies using the same polymer type and activities such as aligning on design choices, material specification and logistic chains to make the cascade work.

MOBILISE LARGE-SCALE, TARGETED 'MOON SHOT' INNOVATIONS

The world's leading businesses, academics and innovators would be invited to come together and define 'moon shot' innovations: focused, practical initiatives with a high potential for significant impact at scale. Areas to look at for such innovations could include the development of bio-benign materials; the development of materials designed to facilitate multilayer reprocessing, such as the use of reversible adhesives based on biomimicry principles; the search for a 'super-polymer' with the functionality of today's polymers and with superior recyclability; chemical marking technologies; and chemical recycling technologies that would overcome some of the environmental and economic issues facing current technologies. Figure 10 provides an overview of example technologies involved in such 'moon shots' and their maturity to date.

FIGURE 10: EXAMPLES OF PROMISING ENABLING TECHNOLOGIES FOR THE NEW PLASTICS ECONOMY AND THEIR LEVEL OF MATURITY



INNOVATION		DESCRIPTION	CURRENT STATE
	Removing additives	Separating additives from recovered polymers to increase recyclate purity	Lab stage: Some technologies exist but with limited application
	Reversible adhesives	Recycling multi-material packaging by designing 'reversible' adhesives that allow for triggered separation of different material layers	Conceptual stage: Innovation needed to develop cost-competitive adhesive
	Super-polymer	Finding a super-polymer that combines functionality and cost with superior after-use properties	Conceptual stage: Innovation needed to develop cost-competitive polymer with desired functional and after-use properties
	Depolymerisation	Recycling plastics to monomer feedstock (building blocks) for virgin-quality polymers	Lab stage: Proven technically possible for polyolefins Limited adoption: Large-scale adoption of depolymerisation for PET hindered by processing costs
	Chemical markers	Sorting plastics by using dye, ink or other additive markers detectable by automated sorting technology	Pilot stage: Food-grade markers available but unproven under commercial operating conditions
	Near infrared	Sorting plastics by using automated optical sorting technology to distinguish polymer types	Fragmented adoption: Large-scale adoption limited by capex demands
	Benign in marine environments	Design plastics that are less harmful to marine environments in case of leakage	Lab stage: First grades of marine degradable plastics (one avenue towards benign materials) already certified as marine degradable — impact of large-scale adoption to be proven
	Benign in fresh water	Design plastics that are less harmful to freshwater environments in case of leakage	Lab stage: Marine degradable plastics theoretically freshwater degradable. One certified product — impact of large-scale adoption to be proven
	GHG-based	Sourcing plastics from carbon in greenhouse gases released by industrial or waste management processes	Pilot stage: CO_2-based proven cost competitive in pilots; methane-based being scaled up to commercial volumes
	Bio-based	Sourcing plastics from carbon in biomass	Limited adoption: Large-scale adoption hindered by limited economies of scale and sophistication of global supply chains

Source: Project MainStream analysis.

DEVELOP INSIGHTS AND BUILD AN ECONOMIC AND SCIENTIFIC EVIDENCE BASE.

Many of the core aspects of plastics material flows and their economics are still poorly understood. While this report, together with a number of other recent efforts, aims to provide initial answers, more research is required. Initial studies could include:

Quantify the socio-economic impact of ocean plastics. Establish measurement tools and a clear fact base. Develop a socio-economic value impact model for ocean plastics. This would enable both the private and public sectors to factor these costs into their decision making.

Explore the scale-up potential of GHG-based plastics. Plastics produced directly from greenhouse gases such as methane, CO_2 and CO are appealing because they could help decouple plastics from the consumption of fossil feedstocks, without using additional land for agriculture. Multiple companies are using GHG-based sources and scaling up quickly. However, the total scale-up potential is unclear at the moment. Therefore, a study aimed at assessing the total scale-up potential (including the economics, availability of feedstocks, polymer types, and applications) and identifying specific ways to scale up production would be helpful.

Explore the potential role of, and boundary conditions for, energy recovery in a transition period. While recovering energy from plastics that cannot (yet) be effectively recycled is in principle a good thing, today's energy recovery solutions have certain drawbacks and risks, as explained above. However, since 100% reuse and recycling rates are unlikely to materialise in the near term, and landfilling is in general not a preferred option, a deep-dive study to assess the potential role of energy recovery in a transition period, as well as the essential boundary conditions, could be useful.

Assess the economic impact of substances of concern (including risks and externalities) and potentially, as a next step, prioritise substances of concern to be designed out.

ENGAGE POLICYMAKERS, IN A COMMON VISION TOWARDS A MORE EFFECTIVE SYSTEM, AND PROVIDE THEM WITH RELEVANT TOOLS, DATA AND INSIGHTS RELATED TO PLASTICS AND PLASTIC PACKAGING.

One specific deliverable could be a plastics toolkit for policymakers, following a structured methodology for assessing opportunities, barriers and policy options to overcome these barriers in transitioning towards the New Plastics Economy. Inspiration could be found in the Ellen MacArthur Foundation report *Delivering the Circular Economy — A Toolkit for Policymakers*.

COORDINATE AND DRIVE COMMUNICATION OF THE NATURE OF TODAY'S SITUATION, THE VISION OF THE NEW PLASTICS ECONOMY, BEST PRACTICES AND INSIGHTS, AS WELL AS SPECIFIC OPPORTUNITIES AND RECOMMENDATIONS, TO STAKEHOLDERS ACTING ALONG THE GLOBAL PLASTIC PACKAGING VALUE CHAIN.

PART II CREATING AN EFFECTIVE AFTER-USE PLASTICS ECONOMY

4 RECYCLING: DRASTICALLY INCREASING ECONOMICS, UPTAKE AND QUALITY THROUGH COMPOUNDING AND MUTUALLY REINFORCING ACTIONS

About 95% of plastic packaging material value, or USD 80–120 billion annually, is lost to the economy after a short first-use cycle. This indicates a significant economic opportunity, even if the industry could only capture part of it. Five levers could — if well coordinated along the global value chain — start the process by jointly enabling a drastic improvement in the economics, uptake, and quality of recycling. These levers are: establish a cross-value chain dialogue mechanism; develop a Global Plastics Protocol to set direction on the redesign and convergence of materials, formats, and after-use systems; focus on key innovation opportunities that have the potential to scale up; enable secondary markets for recycled materials; and explore the enabling role of policy.

4.1 CROSS-VALUE CHAIN ACTION IS REQUIRED TO CAPTURE THE OPPORTUNITY

Today — more than 40 years after the introduction of the first universal recycling symbol — only 14% of plastic packaging is collected for recycling, even though almost all plastics used for packaging are mechanically recyclable with little or no quality impairment.[77] Plastics that do get recycled are mostly recycled into lower-value applications that represent their final use, as they cannot be recycled again (economically). Three broad types of recycling can be distinguished: mechanical closed-loop, mechanical open-loop, and chemical recycling (see Box 3 for definitions). Today, the vast majority of plastic packaging recycling is mechanical open-loop recycling — meaning that materials are sorted, shredded, and reprocessed into lower-value, typically non-packaging applications. For example, around 80% of recycled PET bottles are turned into polyester fibres for carpet, clothing and other non-packaging applications.[78] Other large applications for open-loop plastics recycling are low-value applications such as ‘plastic lumber’, plastic pipes, and waste collection bags. These applications are typically not (economically) recyclable after use, so open-loop recycling today often adds just one additional use cycle rather than creating a truly circular model.

Box 3: Different types of recycling

A key principle of the circular economy is that products and materials are circulated at their highest value at all times (see Chapter 2 for more details). In the technical cycle, this implies that plastic packaging is reused when possible (circulating the packaging product), then recycled (circulating the packaging materials). Within recycling, this principle results in a general order of preference:

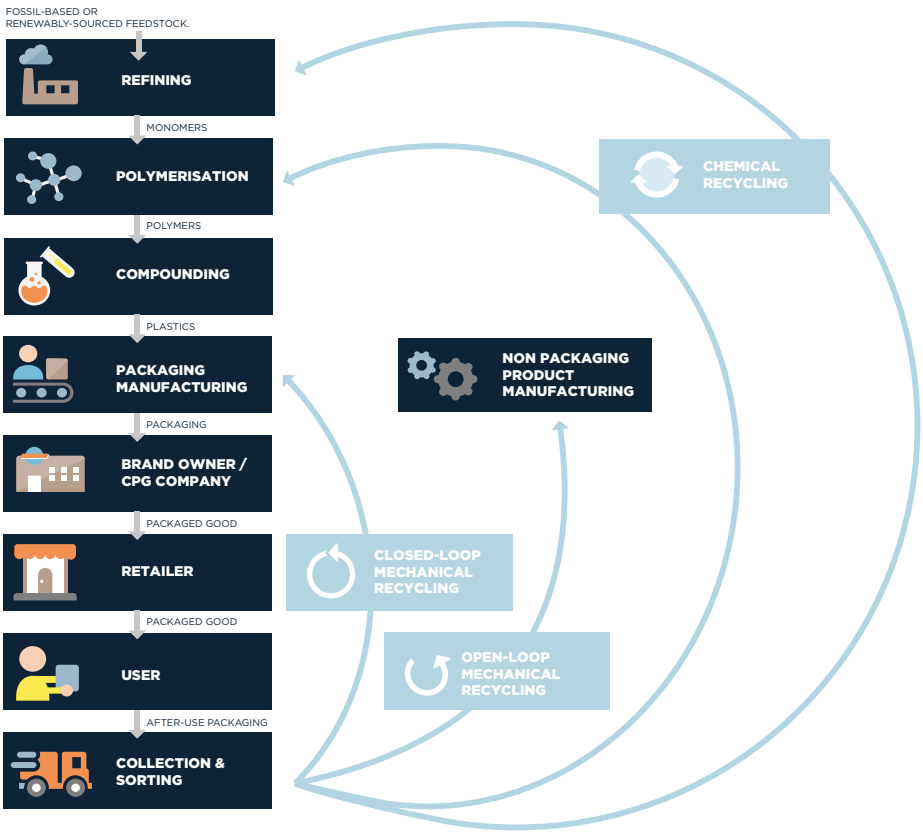
1. **Mechanical recycling in closed loops.** This is the most value-preserving loop. *Mechanical* recycling keeps polymers intact and hence preserves more value than chemical recycling, where polymers are broken down. *Closed-loop* mechanical recycling keeps the quality of the materials at a similar level by cycling materials into the same application (e.g. from PET bottle to PET bottle) or into applications requiring materials of similar quality. As such, mechanical closed-loop recycling not only preserves the value of the material, it also maintains the range of possible applications in future, additional loops.

2. **Mechanical recycling in open loops ('cascading').** Given the inherent quality loss during mechanical recycling,[79] closed-loop mechanical recycling cannot continue indefinitely. Open-loop recycling plays an important role as well. In open-loop mechanical recycling, polymers are also kept intact, but the degraded quality and/or material properties require applications with lower demands. Cascading to the highest-value applications each cycle could help maximise value preservation and the number of possible loops.

3. **Chemical recycling.** Chemical recycling breaks down polymers into individual monomers or other hydrocarbon products that can then serve as building blocks or feedstock to produce polymers again. As such, it is less value preserving than mechanical recycling. Chemical recycling technologies are not yet widespread and/or not yet economically viable for most common packaging plastics. However, as they could enable after-use plastics to be upcycled into virgin-quality polymers again, they could become an option for materials for which mechanical recycling is not possible (e.g. most multi-material packaging or plastics that cannot be cascaded any further).

The rank order above offers a general order of preference and target state to innovate towards, but, as pointed out in Part I of this report, should not be seen as a strict hierarchy for determining the best option for every single piece of packaging *today* (see also Figure 11 below).

FIGURE 11: OVERVIEW OF RECYCLING TYPES



Source: Project MainStream analysis.

The collected-for-recycling rate of 14% is a global average. It varies tremendously by format and material type, indicating the importance of format and material choice in creating a working after-use economy. Certain material/format combinations — mainly PET bottles, HDPE bottles, and post-commercial films — are already recycled at relatively high volumes today. More than half of PET bottles, for example, are collected for recycling globally, reaching 80–90% in certain markets.[80] Most other packaging types are not yet recycled at scale (see Figure 12). The reason for these differences in recycling rates is the extent to which the format and material design enables high-purity after-use streams at competitive prices and in significant volumes, a key driver for recycling economics.[81] Take the example of beverage bottles. Large and affordable pure streams of after-use bottles can be supplied because they are easily recognisable by the citizen — for source separation — as well as by manual or automated sorting facilities. They are typically not significantly contaminated with hard-to-remove food residues, and the chemical composition varies very little between bottles. Another example is post-commercial mono-material films, which can typically be collected in bulk as a clean, mono-material after-use stream. Other packaging types, on the other hand, often have a very wide range of chemical compositions and formats, each of them available in limited volumes. This makes it harder to separate them into clean, mono-material streams at acceptable cost and in significant volumes. Multi-material packaging, while offering significant functional benefits, poses another challenge from a recycling perspective (see Box 4).

Box 4: Multi-material packaging: Definition, advantages, and after-use challenges

Multi-material packaging consists of multiple material types that cannot currently be easily and mechanically separated (a PET bottle with a PP cap is not considered a multi-material packaging in this context). Such packaging items can be blends of different plastics or products combining layers of different materials — different plastic types, thin metal foils or coatings and/or layers of paper or cardboard.

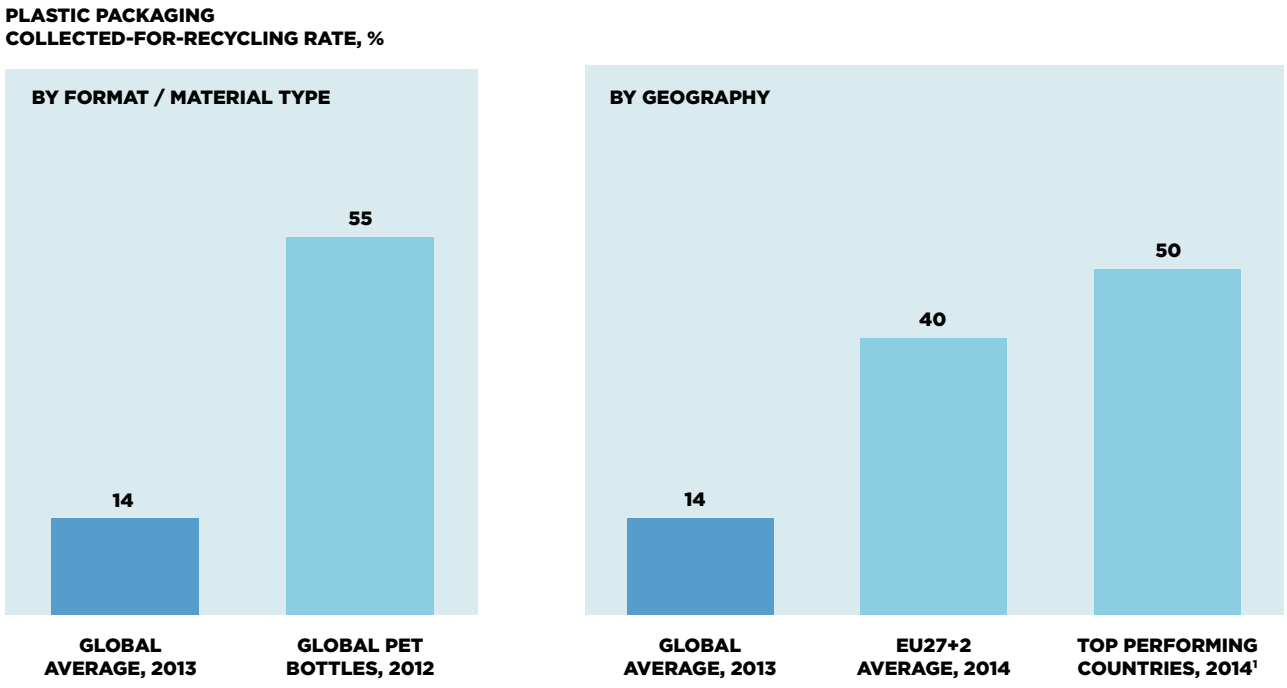
The advantage of multi-material packaging products is that they can combine the functional properties of different materials in one packaging item. As such, multi-material packaging is a fast-growing market today. Some of the best-known applications are multilayer films (e.g. crisp bags), stand-up pouches, tubes (e.g. toothpaste), and plastic-aluminium beverage cartons.

As it is currently not possible to separate the different materials in multi-material plastics economically, mechanical recycling into high-purity mono-material recyclates is not possible. Increasingly, recyclers are turning to additives called *compatibilisers*, already well-known to primary resin producers that want to achieve the combined properties of hard-to-blend polymers. In the recycling process, these additives may be used to blend normally incompatible resins — multi-material packaging or inseparable materials, as may be found in the residual fraction coming out a sorting process — and hence allow for mechanical recycling of previously discarded materials, albeit into low-value applications.[82]

In future, chemical separation or chemical recycling could offer solutions for multi-material products, provided the technology is further developed.

The collected-for-recycling rates contributing to the 14% global average also vary considerably by geography, indicating the importance of after-use infrastructure and policy in creating a working after-use economy. The approx. 50% rate for plastic packaging collected for recycling achieved in Germany and the Czech Republic[83] in 2014 is more than three times higher than the global average, and 25% higher than the EU average of 40%[84] (see Figure 12). While this does not mean that 50% actually gets recycled, and while measurement methods do differ between countries, the approx. 50% rate does indicate the influence of the choice of after-use infrastructure and policy on recycling rates.

FIGURE 12: RECYCLING RATES FOR DIFFERENT MATERIAL-FORMAT COMBINATIONS AND GEOGRAPHIES



Note: Reporting on recycling rates is not harmonised across different countries. Most often the reported numbers represent the share of materials collected for recycling. Given the average recycling yield of 70–78%[2], this is not equal to the share of after-use plastics that is actually recycled.

1 Czech Republic (~52%), Germany (~50%), Slovenia and Sweden (~47%), Ireland and Estonia (~46%), Netherlands (~45%)

2 Due to contamination, moisture and sorting mistakes, not all of this weight is being eventually recycled. Deloitte, *Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment* (2015).

Source: Project Mainstream analysis; Consultic data reported in PlasticsEurope, *Plastics – the Fact 2015* (2015); EU27+2 2014 Plastic packaging recycling rate provided by PlasticsEurope upon request.

Only 35–40% of the virgin material value of plastics collected for recycling is currently retained for a next use cycle, indicating the need to complement efforts to increase the collected-for-recycling rates with actions to drastically improve recycling quality and economics. With an average recycling yield of ~70–78%,[85] and an average price discount for recycled plastics of 50% versus virgin prices,[86] only 35–40% of the virgin material value of plastics collected-for-recycling rates is currently retained for a next use cycle.

Coordinated and compounding action is needed across the global value chain, from design to recyclate markets, in order to increase recycling economics, uptake, and quality. These actions could include:

- **Establish a cross-value chain dialogue mechanism,** including players across the global value chain, to steer and coordinate action.
- **Develop a Global Plastics Protocol** to set direction on the redesign and convergence of materials, formats, and after-use systems to substantially improve collection, sorting, and reprocessing yields, quality, and economics, while allowing for regional differences and continued innovation.
- **Pursue technological innovation opportunities that have the potential to scale up**, such as investments in new or improved materials, sorting and reprocessing.
- **Enable secondary markets for recycled materials** by making composition more transparent and implementing and scaling up matchmaking mechanisms, industry commitments and/or policy interventions.
- **Explore the enabling role of policy.**

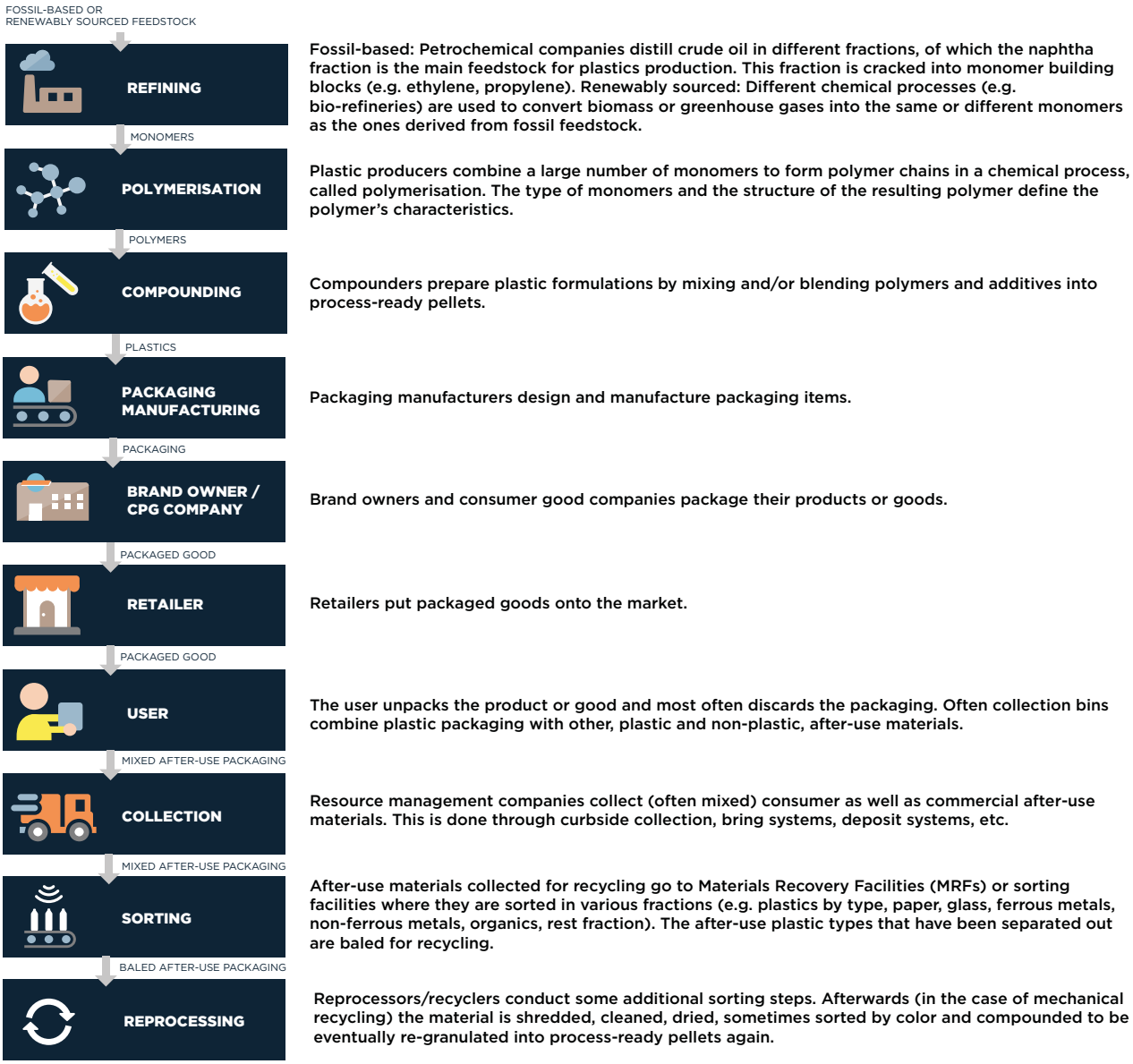
An initial discussion of what these actions could entail can be found in the sections below.

4.2 ESTABLISH A CROSS-VALUE CHAIN DIALOGUE MECHANISM

A cross-value chain dialogue mechanism, including players across the global value chain would be required to overcome existing fragmentation. Today, innovation in the plastics value chain happens largely in an uncoordinated and fragmented way. The development and introduction of new packaging materials and formats across global supply and distribution chains is happening far faster than, and is largely disconnected from, the development and deployment of corresponding

after-use systems and infrastructure. At the same time, hundreds, if not thousands, of small-scale local initiatives are launched each year, focused on areas such as improving collection schemes and installing new sorting and reprocessing technologies. A first step towards improved coordination and a prerequisite for systemic change would therefore be setting up a global cross-value chain dialogue mechanism that brings together the different actors across the global value chain (see Figure 13 below).

FIGURE 13: PLASTIC PACKAGING VALUE CHAIN



Source: PlasticsEurope website (January 2016); Plastics Recyclers Europe website (January 2016); Project MainStream analysis.

4.3 DEVELOP A GLOBAL PLASTICS PROTOCOL TO SET DIRECTION ON THE REDESIGN AND CONVERGENCE OF MATERIALS, FORMATS, AND AFTER-USE SYSTEMS

Today's plastics economy is highly fragmented. The lack of standards and coordination across the value chain has allowed the proliferation of materials, formats, labelling, collection schemes, and sorting and reprocessing systems, which collectively hamper the development of effective markets. While there are many innovation and improvement efforts that show potential, to date these have proven to be too fragmented and uncoordinated to have impact at scale. A global plastics protocol would be needed to provide a core set of standards as the basis on which to innovate. It would need to be a cross-value chain effort, building upon the dialogue mechanism described above. The protocol could provide guidance on design, labelling, marking, after-use infrastructure and

secondary markets, allowing for regional differences and innovation, in order to overcome the existing fragmentation and to fundamentally shift after-use collection and reprocessing economics and market effectiveness. Such guidance would need to go beyond incremental improvements and investigate fundamental questions about the design of products and materials as well as the way after-use systems are set up. This report lays out initial perspectives on guidance for two critical aspects of a global plastics protocol: (i) develop and facilitate adoption of global plastic packaging guidelines, and (ii) develop and facilitate adoption of collection and sorting guidelines.

4.3.1 Develop and facilitate adoption of global plastic packaging design guidelines

As discussed in Section 4.1, the wide differences in recycling rates between different material-format combinations indicate the importance of design to enhance after-use economics. Design choices directly impact the complexity and economics of after-use processes in different ways:

Sorting: Packaging items consisting of different elements, such as labels, caps, glues, or different material layers, can result in separation challenges. Some polymer types can also be hard to separate, such as PVC from PET after shredding, or oxo-degradable materials from their non-degradable counterparts. Some formats are more challenging to handle, such as small-format packaging and films. Sorting machines can find it difficult to identify packaging items, e.g. bottles covered in full-body sleeves.

Cleaning: Cleaning challenges not only arise from contamination but can also be linked to design choices. Certain types of glues and inks might be difficult or impossible to remove from the plastic with common cleaning technology and could require investment in more extensive cleaning. Also designing packaging so that no or minimal product residues remain after use can facilitate cleaning processes.

Scale: Economic challenges can arise if there are only small volumes of certain formats or materials, as it may not be worth investing in the relevant sorting and/or reprocessing technology.

To be successful, global plastic packaging design guidelines would need to be:

- **Industry driven.** The development of packaging design guidelines would need to be supported and driven by industry, involving major players along the entire value chain (from design to recovery). The effort would need to take into account the key challenges and performance requirements in each step of the chain.
- **Global**. Plastic packaging material flows are global: a design decision in Europe might influence the format and material composition of a packaging item used in the United States and eventually reprocessed in China. As such, the development of guidelines would need to be globally coordinated, allowing for regional variations. Adoption could be driven by a voluntary industry agreement, for example by building upon existing global platforms such as the Consumer Goods Forum. Global design guidelines could also offer a basis for policymakers wanting to set up incentive measures. One example of such measures can be observed in France, where fees paid into the Extended Producer Responsibility compliance mechanism can reflect penalties for designs that are known to impede high-quality recycling (e.g. PET bottles with PVC or aluminium labels or caps).[87] Basing such measures on a set of global design guidelines would ensure that producers can design towards one standard and do not have to adapt to a patchwork of regional regulations.
- **Ongoing and allowing for innovation.** Defining design guidelines is not a one-off task, but an ongoing effort. Innovation in design, production, sorting, washing, and recycling technologies continuously pushes the boundaries of what is technically and economically feasible. New packaging solutions would need to be tested and the guidelines updated accordingly.
- **Coordinated with the development of after-use infrastructure.** The design guidelines would need to be aligned with the global guidelines for collection, sorting and reprocessing discussed in the following section.

As a starting point, the development of global design guidelines could focus on replacing formats and/or material designs that impede sorting and/or reprocessing with known, effective alternatives, and on leveraging existing design guidelines and experience in setting up industry-wide initiatives.

In various cases, format and/or material designs that impede sorting and/or recycling can be replaced with existing alternatives, with higher chances of being recycled and without significantly impacting performance, costs or other criteria. For example, for a material like PVC (that can inhibit PET recycling) there already exist alternatives for most of its packaging applications (see Box 5). Also, suppliers to the packaging industry have developed easily recyclable solutions ranging from entire packaging formats to lids, seals, caps, glues, inks, and labels.

For cases where no clear solutions exist with similar cost and functional performance, R&D and innovation could be focused on developing alternatives (see Section 4.4 below).

Box 5: Selected examples of hard-to-recycle materials and corresponding solutions

PVC

PVC is a very versatile and cost-efficient material. It is used in several packaging applications such as rigid film, flexible film, closures, blisters, and presentation trays. Globally, PVC represents about 5% of the plastic packaging market.

However, the use of PVC in packaging applications has major drawbacks (for non-packaging applications such as piping or window frames, PVC could continue to play an important role). In addition to the concerns addressed in Chapter 7, the presence of PVC in PET recycling leads to significant quality concerns. Even at concentrations of just 0.005% by weight, PVC can form acids that break down PET.[88] This causes the recycled PET to become brittle and yellowish in colour, compromising two of the most important aspects of PET: impact strength and clarity. There are several ways that PVC can end up in the PET recycling stream, including (i) PVC bottles resembling PET bottles; (ii) PVC safety seals, labels, and sleeves that are used on PET bottles, and (iii) PVC liners that are used inside bottle caps and closures.

Alternatives do exist, and PVC is already being replaced in more and more packaging applications: PVC bottles are in decline; solutions based on extruded polyethylene foam or more advanced cone-liner types made from LDPE can replace PVC cap liners; and for labels PE and PP solutions are available. PVC could also be phased out in non-PET-bottle-related packaging applications: PVC is replaced by LLDPE in pallet stretch-wrap; PET has found use as blister packaging. Given the clear drawbacks and available alternatives, companies like Unilever and Marks & Spencer have already phased out PVC from their packaging, and PVC bans or restrictions apply in multiple cities and countries around the world.[89]

(Expanded) Polystyrene or (E)PS

Polystyrene makes up about 3% of today's plastic packaging market.[90] Its main applications in non-expanded format are trays, cups, and bottles while in expanded format it is mainly used for disposable food packaging such as hot-beverage cups and clamshells, food trays and for cushioning and 'packaging peanuts' to protect objects during shipping. In addition to packaging EPS is used in large volumes as insulation material.[91]

PS has very low recycling rates today — while it is technically possible to recycle, if significant volumes of clean material are available, this prerequisite is seldom fulfilled. First, the material is often contaminated as many major applications of PS are food-related. Second, especially EPS is very bulky (low density), which has direct implications for collection and transport costs. Therefore, very few regions around the world collect EPS as part of the recyclables stream.

If the barriers for effective and economically viable collection, sorting, cleaning and recycling of PS cannot be overcome, other packaging solutions could be considered. More recyclable plastics, such as PET and PP and, to a lesser extent, polylactic acid (PLA) are already substituting general-purpose PS in applications like trays and yoghurt cups. Paper and cardboard solutions are common alternatives for take-away food packaging. PS as shipment protection is already substituted by Ecovative's mushroom-based Myco Foam[92] — commercialised by Sealed Air as Restore® Mushroom® Packaging[93] and used by companies like Dell — or biodegradable moulded pulp.[94] Companies like Marks & Spencer have largely phased PS out of their products and packaging.[95] McDonald's began to phase out its iconic clamshell foam hamburger box in 1990 and is now phasing out styrofoam beverage cups. More than 70 cities across the United States are already enforcing bans on EPS foodware, EPS or even PS — or have set dates for the ban to start — including Washington DC, Minneapolis, San Francisco, Oakland, Portland, Albany, and Seattle.[96]

Labels

Labels fulfil an important role in packaging in terms of both branding and information. There are, however, certain types of labels that can cause problems during the recycling process. Full-colour full-body sleeves for example can cause errors during sorting processes. Paper labels on plastic containers — if not removed — pulp in the washing phase, leaving adhesives residue or disaggregating with its fibres contaminating the plastic stream.[97] Moreover, some types of glue do not dissolve in water and, therefore, cannot be removed from the container. These issues can be addressed by switching to alternatives: plastic labels that cover no more than 40% of the container's surface and full-body sleeves with sufficient transparency and water-soluble glues.[98]

Several organisations have published important design guidelines tailored to different packaging formats (e.g. bottles, trays, pots), and/or converted them into practical tools.[99] One existing example of an industry-wide initiative to develop such design guidelines for one specific packaging format is the European PET Bottle Platform (EPBP). This voluntary organisation publishes continuously updated design guidelines for PET bottles, taking into account the latest innovations and knowledge. Furthermore, it has established a process to assess the potential impact of new design or material

solutions on the sorting and recycling of the bottles. This process can lead to the publication of an EPBP statement of conformity with recycling processes. This system has moved many large companies to require EPBP statements from all their suppliers of PET-bottle-related solutions (including materials, additives, labels, caps). The main driver for companies to support and leverage this system is to protect and improve the high PET bottle recycling rates — one of the key advantages PET bottles have over other materials and formats — and to be able to claim high effective recycling rates of the packaging they put on the market.[100] Another example of a global industry-wide packaging initiative is the Global Protocol for Packaging Sustainability — a document developed by the Consumer Goods Forum that provides metrics and a common language for packaging designers to use in discussions and assessments of the relative sustainability of packaging.[101] Also the ISO's standards on packaging and the environment (ISO 18601 to 18606) are examples of global guidelines that could be built upon.

Global plastic packaging design guidelines would also need to go beyond traditional efforts and incremental improvements, and investigate fundamental questions about how plastic packaging could be designed to achieve better economic and environmental system outcomes. Examples of questions that could be investigated are: *To what extent could plastic packaging be designed with a significantly smaller set of material/additive combinations, and what would be the resulting economic benefits? What would be the potential for designing out small-format/ low-value plastic packaging such as tear-offs with challenging after-use economics and a high likelihood of leakage? What would be the economic benefits of harmonising the labelling and chemical marking across plastic packaging and aligning these standards with after-use separation and sorting systems?*

4.3.2 Develop and facilitate adoption of collection and sorting guidelines

Guidelines that initiate convergence towards a set of global collection and sorting archetypes, allowing for regional variation but building upon a set of common principles, as well as investigating fundamental questions about the way (plastic) material streams are collected and sorted for reprocessing would be a critical part of substantially improving recycling economics, quality and uptake. This section provides an initial exploration of these topics, mostly from a developed market perspective.

Convergence towards a set of global collection and sorting archetypes, allowing for regional variation but building upon a set of common principles, would offer packaging designers a common system to work towards, create clarity for citizens, and enable the capture of economies of scale.

Convergence of after-use systems would enable global design principles to be developed accordingly — making it highly synergetic with the design guidelines explained above. It would enable innovations in sorting, labelling, tagging, and other technologies to be more focused and to scale up rapidly. For citizens, having the same bins and sorting rules at home, at work, and in public spaces could lead to more clarity and fewer sorting mistakes. Cities and companies active in collection and sorting would be able to benefit more easily from economies of scale and share best practices across their facilities.

Achieving economies of scale through convergence. A wide range of studies has confirmed the potential for economies of scale in sorting activities.[102] A study done by PwC in 2014 for example, based on data from French sorting facilities, indicated reductions of plastic sorting cost per tonne of 35% and 43% for plastic sorting facilities processing 30,000 and 60,000 tonnes per year versus a plant processing 10,000 tonnes per year.[103]

Economies of scale can be achieved in several ways:

- By consolidating smaller local MRFs into larger-scale MRFs
- By source separating plastic waste and sorting it in dedicated larger-scale PRFs (plastic recovery facilities)
- By separating mixed recyclables in local MRFs and sending plastic fractions to dedicated larger-scale PRFs

Next to pure economies of scale, a transition towards larger-scale sorting facilities could help justify investments in advanced sorting technology. An academic study on sorting economics concluded that economies of scale allow larger plants to make use of the latest technology upgrades — such as advances in process control and automated sorting — while at the same time achieving a greater level of diversification in recovered products.[104] Furthermore, a more consolidated network of sorting facilities can enable the separation of more different fractions while keeping significant volumes of each. Finally, a reduced number of facilities could lead to a more harmonised quality of bales supplied to the market, and could allow for better control and optimisation of the resource streams in the economy.

Transportation and investment challenges. There are some challenges that need to be considered to capture economies of scale. First, a more consolidated network of sorting facilities could lead to increased transportation. A more detailed assessment would need to compare the environmental and economic benefits of increased recycling rates and the additional transport. Such

an assessment would depend on local factors (e.g. SUEZ's Rotterdam plant leverages waterways for long-distance transport) and would need to be forward looking, considering trends such as electrification and autonomous driving that are expected to break through at scale in the next decade, as well as the expected evolution in material flow volumes. Second, significant investment could be required in new facility development. However, expert interviews have indicated that various sorting companies are already looking to set up collaborations in specific regions to avoid stranded assets, for example by replacing two plants that need renovation with one new larger facility.

Current examples of successful convergence. Several organisations and governments are already taking action to increase convergence. The Scottish government recently announced The Household Recycling Charter and associated Code of Practice, aiming to move towards a single system for recycling, citing the potential to unlock value in waste collection while creating local jobs.[105] The charter sets out principles that councils will voluntarily commit to. These principles are expected to lead to greater consistency in the materials collected for recycling, as well as alignment of policies, operations and communications in line with the established good practice. Multi-Material BC (MMBC) has also harmonised and redesigned collection and post-collection activities in British Columbia. For collection, it has developed agreements with local governments, First Nations and private collectors to operate curbside, multi-family and depot collection programmes in different communities. While collectors make operational decisions about their programmes, the set of materials accepted by MMBC is harmonised. 'This helps alleviate confusion, allows MMBC to conduct larger promotion and education campaigns across all communities and means that residents don't have to re-educate themselves when they move to different communities', Allen Langdon, Managing Director of MMBC, says. Post-collection an approach has been developed to service the entire province as a single after-use shed. This approach allows the province to achieve productivity previously unavailable to residential recycling programmes. For example, by sorting all containers in one central high-performing facility rather than investing in retrofitting 4 or 5 traditional MRFs. In addition, it has enabled MMBC to start leveraging this system as a platform for engaging producers in real-time trials and studies to test and support new innovations in packaging.

Scale economies already realised in some regions. The shift towards economies of scale can also already be observed in different regions. Before the year 2000, Germany had around 250 plants of small to medium capacity (largest 40,000 tonnes per year) sorting lightweight packaging (including plastic, paper, metal packaging). In the following decade, significant technological advancement was accompanied by a strong concentration in capacity. By 2011, the number of plants had fallen to 92 (biggest capacity 100,000–120,000 tonnes per year).[106] In France, there is also a debate around consolidating smaller sorting plants. A study done by PwC in 2014 concluded that an international comparison of the average size and costs of sorting facilities indicated that the current French sorting plants are too small and not equipped to benefit from economies of scale and advanced technologies available.[107] Other examples of companies reaping the benefits of economies of scale are SUEZ, which has built a 80,000 tonnes per annum PRF facility in Rotterdam, processing 70% of all source-separated plastic packaging in the Netherlands,[108] and Veolia, which is operating a plant near London, which processes 50,000 tonnes of plastics per year.

Efforts to develop guidelines for collection and sorting systems would need to go beyond convergence and rolling out of current best practices, and investigate fundamental questions about the way (plastic) material streams are collected and sorted for reprocessing, taking into account future trends such as urbanisation, e-commerce, renewable energy, autonomous driving collection vehicles and the evolution of plastic packaging (and other material) volumes. These questions could include: *If a new city would be designed from scratch, how would the collection and sorting system look like? Would waste be collected by truck or by drone, would all houses be connected with a piping system for waste transport like the South Korean city of Songdo[109] or would it look even more different? What would be the economic benefits of harmonising the labelling and chemical marking across plastic packaging and aligning these standards with after-use separation and sorting systems? How will the material composition of waste likely evolve taking into account trends like light-weighting, digitalisation, and e-commerce? What would be the impact on collection systems and costs once trucks drive autonomously?*

Guidelines for collection and sorting systems would likely build on two principles: source separation and comprehensive collection for recycling.

Source separation. As materials designed for the biological cycle and materials designed for the technical cycle need to follow different after-use pathways, they need to be separated. Even in the short term, for systems still landfilling or incinerating waste in large-scale mixed solid waste incinerators, separating organic and technical after-use streams is worthwhile. It eliminates the incineration of mixed organic and non-organic waste, which is an inefficient energy recovery process.[110] Diverting organic waste from landfill reduces the amount of methane generated in a landfill, avoiding direct methane emissions for landfills without methane capture infrastructure.

The separation can be done at the source (e.g. different bins in households or at drop-off points) or later on in sorting facilities. Source separation of organic waste from recyclable materials could increase the cost of separate collection, but would lead to significantly lower sorting costs. In terms of quality, source separation has the benefit that it avoids contamination between the biological and the technical cycle during collection, improving the ease, quality and the economics of recycling for technical materials and at the same time facilitating the safe return of biological nutrients to the biosphere after composting or anaerobic digestion.

A study for the EU Commission comparing different waste management options from a greenhouse gas perspective concluded that, *'overall, source segregation of MSW [municipal solid waste] followed by recycling (for paper, metals, textiles, and plastics) and composting/AD (for putrescible wastes) gives the lowest net flux of greenhouse gases, compared with other options for the treatment of bulk MSW'.*[111]

Comprehensive collection and sorting for recycling. Today, many countries with established collection systems focus on 'picking the gold nuggets', collecting plastic packaging with mature recycling markets (e.g. PET and HDPE bottles) for recycling, while the remaining packaging is collected as part of the residual waste stream and sent directly to landfill or incineration. This leads to high recycling rates for these 'gold nuggets', but limits the overall recycling potential — bottles only represent one-third of total post-consumer plastic packaging[112] — and perpetuates a stalemate: the lack of collection and sorting infrastructure disincentivises designing for recyclability and the development of reprocessing infrastructure, while the lack of design for recyclability outside a few 'gold nuggets' and the lack of reprocessing infrastructure dis-incentivises the build-up of comprehensive collection and sorting infrastructure. Coordinated cross-value chain action could enable overcoming this stalemate.

More and more regions are increasing the range of packaging items that are collected for recycling. In Germany, all plastic packaging is collected in the recycling bin as part of the Green Dot system or through dedicated collection centres.[113] In the Netherlands, municipalities are shifting to the segregated collection of all plastic packaging (with the exception of large PET bottles, which are subject to a deposit fee), through a collaboration with Plastic Heroes, an initiative of the packaging producers.[114] In Belgium, municipalities have launched pilots to expand the range from PET bottles, HDPE bottles and jars to other plastic packaging such as pots, trays, films, and bags.[115] The comprehensive collection of plastic packaging for recycling is also important in public spaces. One third of bottled beverages are consumed away from home, for example.[116]

There remain important questions about the set-up of collection and sorting systems that would need to be further investigated.

- **Collection.** *What are the respective benefits of curbside collection versus take-back systems? What could be the role of deposit systems for specific packaging items? Could the transport costs of bulky after-use plastics be reduced by installing a shredding machine on each collection truck, now that the latest NIR-based sorting technology can handle plastic flakes as small as 2 mm?*[117] *What would be the impact on collection costs of driverless trucks, which are already being tested in real-word traffic today?*[118] *Or would we need to move away from trucks to drones or to piping systems for waste transport like the South Korean city of Songdo?*[119]

- **Sorting.** *What would need to be the role of source separation by citizens versus centralised sorting, and of manual versus automated central sorting, taking into account economic and cultural differences between regions? On automated sorting, would the industry need to continue the current path of improving technology to recognise plastic types, or would it need to further explore the option of 'attaching' information to each packaging item through chemical markers, barcodes or chips, so that sorting facilities would only need to read the information (also see the following section for sorting technology innovation)? Would it be sufficient to identify the resin type, or could recognising the brand, manufacturer and detailed chemical composition of the item open up new opportunities?*

4.4 PURSUE TECHNOLOGICAL INNOVATION OPPORTUNITIES THAT HAVE THE POTENTIAL TO SCALE UP

Technological innovation could enable cities and regions to achieve recycling rates, quality, and economics beyond what is feasible today. Industry-wide coordination and collaboration will be required to capture the full potential.

4.4.1 Innovate towards material and format designs for improved recyclability, without sacrificing functionality

Developing new materials could, if coupled with adapted after-use infrastructure, result in significant economic and environmental benefits. Finding a plastic type that has the required properties to be

used in a wide variety of packaging applications while also offering superior recycling properties, could transform the industry. This search for new materials could be inspired by, for example, the recycling properties of Nylon 6 or by biomimicry.[120]

Nylon 6 is a thermoplastic material with great recycling properties. It can be 'infinitely' recycled in a closed-loop system, using a chemical recycling process (see Box 6). This process has been used in the carpet industry since the 1990s,[121] where after-use Nylon 6 carpet face fibres are converted into virgin-quality caprolactam, the monomer building block of Nylon 6.[122] *Can material innovation lead to a similar 'infinite' closed-loop system in the packaging industry? Can Nylon 6 inspire our search for materials combining similar recycling properties with the right functional properties to be widely used and scaled up as a packaging material?*

Box 6: Nylon 6: A potential inspiration source as a material with 'infinite' closed loops

Nylon 6, the most popular nylon grade, is a polymer built up by synthesising caprolactam, its monomer building block. Nylon 6 is mainly used as fibres for various applications ranging from textiles to tyre cords. Non-fibre applications include various plastic parts (e.g. for automotive, electrical, and electronics parts) and plastic films that are mainly used in packaging.

Nylon 6 is one of the very few polymers for which a closed-loop chemical recycling process is already in place on an industrial scale.[123] Since the 1990s, end-of-life Nylon 6-based carpet scrap has been depolymerised into virgin-quality caprolactam. Today Aquafil applies this technology on an industrial scale. Their Econyl® polymer contains 100% recycled Nylon 6 content, of which at least 50% from post-consumer sources such as carpets or fishing nets.[124] For each tonne of caprolactam produced in the ECONYL® process, 16.2 GJ of energy and 7 barrels of oil are saved, 1.1 tonnes of waste is eliminated and 4.1 tonnes of CO_2e are avoided compared to the traditional fossil-based production route.[125]

While Nylon 6 can offer inspiration, its direct application in plastic packaging is challenging. Due to its relatively high price and functional properties nylon is currently only a niche packaging polymer accounting for less than 1%[126] of the overall plastic packaging market. Even though Nylon 6 is used for the packaging of high-value food products including meat, cheese, pasta, and convenience food,[127] the majority of such applications combine Nylon 6 with commodity plastics (mainly PE) in multilayer films to make up for nylon's poor moisture barriers.[128] Such multilayer films can currently not be effectively recycled.

Biomimicry could inspire the development of new packaging materials. Biomimicry is an approach to innovation that seeks solutions to human challenges by emulating nature's time-tested patterns and strategies.[129] While humans have developed a plethora of synthetic materials, technology is not able to provide the wide range of functionalities and complexity of polymers that nature does with only a limited amount of building blocks.[130] The precise assembly of natural polymers underlies their selectivities in function, which have been tuned through successive cycles of evolution against an enormous diversity of fitness functions.[131]

Cellulose and starch are instructive examples. Cellulose, found in wood, cotton and hemp, is strong, does not dissolve in water and can't be digested by humans. Starch, on the other hand, found in potatoes, corn, rice, and grains, dissolves in water and is digested by humans and other species as an important source of energy. Yet both these polymers are built up from the same monomer — glucose — combined in different 3D structures. Well-designed molecular structure is also the reason for natural polymers' exceptional functional properties. Spider silk, for example, combines high strength and elasticity and is therefore a model polymer for development of high-performance fibres.[132] *Could any of these examples inspire us to deploy more controlled assembly of synthetic monomers in order to develop new highly functional packaging materials?*[133]

One particular challenge for technological design innovation is multi-material packaging. Recycling options are currently limited for this fast-growing packaging segment (see Box 4). To find solutions for this growing segment, the following R&D pathways could be considered:

- **Develop mono-material solutions that deliver similar performance.** For non-barrier multilayer pouches for example, Dow developed a polyethylene-only stand-up pouch.[134] Amcor Flexibles Asia Pacific is conducting research in the use of single-layer films to replace multilayer packaging for certain applications.[135]
- **Develop multi-material packaging or separation technologies that enable the separation of the different materials after use.** For example through reversible adhesives based on biomimicry principles.

Alongside of these design options, parallel efforts on separation (such as recent developments by Saperatec[136]) and reprocessing could be made to enable multi-material recycling.

4.4.2 Innovate in sorting technology to provide high-purity mono-material after-use plastic streams

Today, sorting facilities (in developed countries) combine mechanical sorting techniques, such as flotation, trommel screens, and magnets, with manual sorting steps to separate several dry fractions such as metals, glass, paper, and plastics. The plastics fraction is unique in the sense that it consists of a variety of polymer types, each with different grades that need to be further separated in order to enable recycling. Given that source separation of many different polymer types and grades by citizens is challenging, plastic sorting technology plays a critical role in making high-purity material streams available for recycling.

Sorting technology innovation is exploring several pathways, each based on different principles. Optical sorting counts on technology to recognise polymer types and grades. Image recognition aims at identifying packaging items through machine vision. Marker technologies add an easily identifiable marker to each packaging item.

Optical sorting technology. Optical sorting technology recognises polymer types by illuminating the material and analysing the reflection spectrum. Near Infrared (NIR) spectroscopy is the most common automated sorting technology used for plastic sorting today. Each NIR machine sorts out one type of material. State-of-the-art plants can have up to 20 NIR sorting machines.[137] Recently, TOMRA developed the AUTOSORT flake sorter that can sort plastic flakes as small as 2 mm to enable a detailed sorting step after shredding.[138] Another unit developed by TOMRA uses an extended wavelength scanner to detect and separate two polymers grades within one polymer group, and can achieve purity rates on both end fractions of close to 100%. This technology is already in place in Australia to separate food-grade and non-food grade materials.[139]

Image recognition. While optical sorting aims to recognise the material or polymer type, image recognition could be deployed to recognise specific packaging items. In the longer term this technology could identify the item as well as the brand. This would open up new perspectives. An image recognition system could be linked to a database holding the main characteristics of each item, and could, for example, be linked to EPR systems to couple the producers' contributions to the real costs of recycling its packaging. To unlock these possibilities, further technological development will be required to identify packaging items at high speed. A 2011 WRAP study tested this technology to detect milk bottles during the HDPE recycling process. Their conclusion: *'The high degree of deformation of the milk-bottles during the recycling process means that a 100% rate of detection is unlikely. Although preliminary, experimental work suggests that a system for achieving good sorting with very low false acceptance in labelling food-grade items could be achieved; such a system would need to incorporate an extensive and updateable training process.'*[140]

Marker technology. Another pathway currently being explored is a system in which packaging contains a marker that can be read by sorting machines. This could range from a barcode to invisible chemical markers. Various pieces of information might be embedded in such markers and communicated across the value chain, thereby unlocking new opportunities. Over the last decades, a range of patents has been published on marker chemistry and related instrumentation. Marker-based detection products are used for the security of high-value articles but no marker-based detection system has yet transitioned into widespread use in the recycling industry.[141] Since 2014, the EU-funded Polymark project has been developing a marker-based system, suitable for large-scale industrial implementation, to reliably detect and sort food-contact PET from a PET bale containing a mixture of food-contact and non-food-contact packaging.[142] The Polymark markers are food-contact approved and can be removed after each use cycle to avoid accumulation. WRAP is also investigating and developing the use of machine-readable fluorescent inks and the associated sorting technology to assist identification of different types of polymers during sorting and recovery for recycling.[143] More broadly (chemical) marker technology could be used in the future to differentiate various types of plastic items, allowing more detailed and/or easier sorting in addition to or as a substitute for current NIR technology. To achieve this, industrial-scale tests are required, and the detection of multiple markers as 'binary code' is still to be developed.

4.4.3 Innovate in reprocessing technologies

While the efforts described in design, collection, and sorting could lead to significant improvements in the purity of after-use plastic packaging streams, these streams will likely never be 100% pure. There will likely always be food or other contamination, some degree of sorting errors, and a range of different additives even if the streams contain single polymers. Therefore, it would be important to continue developing reprocessing technologies to enable the recycling of materials that cannot be processed into high-quality products today and improve the quality of recyclates to allow for more subsequent loops. This could be done by:

Improving the quality of mechanical recycling processes and the range of materials that can be mechanically recycled into high-quality recycled materials.

Further developing and scaling up chemical recycling technologies to enable upcycling to virgin quality and establish 'infinite' loops. This would offer

solutions for multi-material packaging and plastics that cannot be further mechanically recycled.

Mechanical recycling. Improving the economics and quality of recycling could be facilitated by, in addition to the levers discussed before, enhancing the recycling process itself, including:

- **Cleaning technologies.** To retain as much value and quality as possible in each mechanical recycling step, intensive cleaning and granular post-sorting steps are required. Recyclers such as Quality Circular Polymers[144] (QCP) is undertaking recycling activities that focus solely on high-quality end products. QCP has invested in more, more advanced, and more expensive cleaning technology in order to produce high-quality, high-value recycled PP and PE. Another option would be to go even further and aim for food-grade-approved recycled polyolefins. Huub Meessen, CEO of QCP, stresses the importance of high-quality recyclates: *'We can only reach a true circular economy for polymers if waste management companies and recyclers invest and innovate in quality. And by doing so, enabling brand owners and plastics convertors to replace "virgin" polymers by circular polymers, also for high-end applications. Higher prices for these products will make up for the extra investments in quality'.*[145] These quality improvements would, of course, be facilitated by the design and sorting levers already mentioned.

- **Chemical extraction of additives.** While cleaning technology removes dirt and contamination that is external to the target material, it can also be advantageous to remove certain additives that are embedded in the material itself. This prevents additives from accumulating over several cycles and might allow to recover (more expensive) additives separately, and improves product purity so that polymers can be more easily processed and targeted to specifications. The German recycler APK[146] has developed a chemical process that is able to extract certain types of additives such as starch and part of the colour pigments. Ideally, further development would enable the design of selective processes that leave in the additives that are desired in the end product and extract the unwanted ones.

- **Chemical separation of different polymer types.** Using the same chemical process, APK is able to separate individual polymer types at the molecular level — currently PE and PP. This chemical separation process keeps the polymers intact, but separates them from each other to enable recycling into mono-material pellets afterwards. The process is particularly well suited to mixed plastics streams for which mechanical processing alone cannot deliver high recycling quality. The most common streams treated by APK today include automotive shredder residue and household waste. Ideally, further development would lead to a solution for multi-material packaging in the future.

Chemical recycling. While mechanical recycling is in general the preferred option, there will always be after-use plastics that cannot or can no longer be mechanically recycled into a valuable product, such as multi-material packaging or materials that have completed their maximum number of cascading cycles. This is where chemical recycling could play a role in closing the loop back to chemical feedstock again, enabling 'infinite' loops. Chemical recycling is not yet applied at large scale. The different technologies each face different challenges to become technically and economically feasible as well as environmentally desirable:

- **Depolymerisation.** Depolymerisation requires further technological improvements to become an economically viable recycling option for after-use plastics that cannot or can no longer be mechanically recycled. Condensation polymers like polyesters (e.g. PET, PLA) and polyamides (e.g. nylon), can be depolymerised through chemolysis with different reagents (e.g. hydrolysis, methanolysis, glycolysis, aminolysis, etc.) to produce mainly the monomers from which they have been produced or other oligomers.[147] These can then be used as building blocks for the production of new polymers. Nylon 6, for example, has been chemically recycled for years (see Box 6). The technology is also available for PET recycling, but only a few industrial-scale plants exist. While breaking the PET chain is relatively easy, separating out the monomers from the colorants and additives is still costly and energy intensive.[148] This makes it especially challenging for coloured PET, and clear PET is often more easily and cost effectively mechanically recycled. However, the Dutch company Ioniqa Technologies has developed a PET depolymerisation process that it claims is *'cost competitive compared to traditional [mechanical] recycling'*. The Ioniqa process takes place at relatively low operating temperatures and is catalysed by their proprietary Magnetic Fluids.[149]

- **Catalytic cracking.** In contrast to polyesters and polyamides, those polymers that have an extended chain of carbon molecules, such as polyolefins (PP and PE), cannot be depolymerised into their monomers with simple chemicals due to the random scission of the carbon chains.[150] The latter characteristic results in a range of carbon chains of different lengths (cracking). To increase the economic viability of catalytic cracking, academic research is mainly focused on developing catalysts that allow for better yield (narrowing down the range of end products), shorter reaction times, and milder conditions (energy requirements).[151] The petrochemical industry has decades of experience in catalyst development aimed at improving the speed, quality, and control of

the polymerisation process in the production of plastics. The question arises whether these experts and their decades of experiments can be leveraged to develop catalysts to better control the chemical process in the other direction, i.e. decomposition.

Current research on depolymerisation and catalytic cracking processes focuses on the conversion of high-purity mono-material plastic feed. However, these materials can often also be mechanically recycled. Given that mechanical recycling is a more value-preserving loop than chemical recycling, requiring significantly less energy, these chemical recycling processes should not compete with mechanical recycling for feedstock. Chemical recycling could, however, become highly complementary with mechanical recycling in the future if a way can be found to process mixed, low-quality or multi-material plastic streams.

- **Pyrolysis.** Today, pyrolysis is mainly used for energy recovery (plastic to fuel) rather than material recovery purposes. The main challenge in using pyrolysis to establish material recovery loops is to find a way to integrate the hydrocarbon output product into the chemical industry as a feedstock. To do this would require either refining the quality of the output or getting existing oil refineries to accept the hydrocarbon wax or oil early on into their refining processes.

  While both options are technologically feasible, the economics are challenging today: refinement of the pyrolysis oil or wax is costly, and selling the hydrocarbon product without further refinement might fail to generate sufficient revenues. Companies like Recycling Technologies, which produces a filtered and purified hydrocarbon wax called Plaxx™, are looking for ways to collaborate with oil refineries to make the best use of this material as a chemical feedstock.

  Alongside such efforts, further optimisation of the pyrolysis process is possible by reducing the energy needed to deliver the process heat. Today, best-in-class plants combust 15–25% of the plastic to deliver the required heat.[152] Driving the process with renewable energy in the future could be another option to explore. One way to achieve both energy savings and the electrification that facilitates the shift to renewable energy sources is the microwave-driven pyrolysis process that is currently used by Enval and Climax Global Energy.[153]
  Despite these hurdles in establishing material recovery loops for plastics, there are certain applications in which pyrolysis could play a role today. For plastic-aluminium laminates, a pyrolysis process has been developed by Enval.[154] For these products, pyrolysis has the advantage that no combustion takes place, which means the aluminium (having a large footprint) is recovered at high quality.

4.5 ENABLE SECONDARY MARKETS FOR RECYCLED MATERIALS

Creating a well-functioning secondary market for recycled materials could accelerate the transition to the New Plastics Economy. This can be achieved by better matching supply and demand through enhanced transparency and matchmaking mechanisms, and by strengthening the pull effect on the demand side through industry commitments and/or policy.

4.5.1 Enable better matching of supply and demand through enhanced transparency and matchmaking mechanisms

To enable effective recyclate markets, it is critical that manufacturers are able to find a supplier that can deliver recyclates with the right specifications, and recyclers are able to find a buyer for their recycled products. It is not only about finding sufficient volumes but also about finding materials with the desired specifications in order to meet manufacturers' performance requirements. Compared with virgin-plastic producers, suppliers of recycled plastics can be somewhat more limited in the material specifications they can deliver, depending on their intake of after-use plastic. So it is critical to have a well-performing market for these materials, with sufficient transparency on material specifications and composition and the associated mechanisms to match supply and demand. This constellation could enable recycled materials to be used in the highest-quality applications possible, which would slow the conventional 'cascading down' process, thereby maximising the number of loops and minimising virgin material requirements.

Increasing the transparency of material composition and specifications is an important step in enabling better matchmaking between supply and demand. Making composition and specifications more transparent would reduce the risk for manufacturers of sourcing recycled plastics with suboptimal performance characteristics and the associated potential for economic, safety, and brand image consequences. Providing reliable and precise information on the specifications could thus boost the trust of manufacturers in recycled feedstock, thereby increasing demand and improving the economics of recycled materials.

A first step could be to introduce more granular standards for recycled plastics. The existing material standards specify only rough categories such as coloured/non-coloured and food-grade/non-food-grade. For large manufacturers, which often need to

source recycled plastics from a number of different smaller suppliers (<50,000–80,000 tonnes per year), these standards do not provide sufficient information to ensure limited variability in material specifications. The lack of transparent material composition, due to insufficient standardisation, increases the risk of — often costly — hiccoughs in the manufacturing process. The current situation is in stark contrast with the virgin-plastics industry, which is largely commoditised and supplies large volumes of standardised materials. In effective recycled plastics markets, the effort to find a supply of recycled materials with the desired specifications should ultimately be roughly similar to the effort necessary to source virgin materials, i.e. low.

Better matching of supply and demand could be facilitated by introducing and scaling up matchmaking mechanisms. An example of this would be using aggregator software or platforms to match both recycler and companies that source recycled content. Such a platform could be inspired by the successful US Materials Marketplace pilot by US BCSD, WBCSD, and the Corporate Eco Forum. This pilot project involved 23 participating companies and identified 2.4 million tonnes of underutilised materials. The set-up included a technical team that was actively looking for synergy opportunities among the participants: 68 synergy opportunities were identified and, at the end of October 2015, 19 business-to-business transactions were underway or being explored. Following the success of this pilot, further expansion of the platform is planned in order to include more materials, geographies and participants.[155]

In October 2014, the Scottish government created The Scottish Materials Brokerage Service — 'a one-stop shop for growing Scotland's reprocessing sector and helping local authorities and the public sector get a better deal for the recycled materials collected from their communities.'[156] The secondary materials market in Scotland is fragmented, and most after-use materials are shipped overseas. The new brokerage service will help match supply with demand for high-value recycled materials. The move will help provide certainty of supply and demand, encouraging external investment in reprocessing plants and municipal investment in collection services, while also creating local jobs.

In addition, suppliers of recycled plastics can tailor their materials directly to the demand and needs of manufacturers. SUEZ, for example, recently launched PLAST'Lab to optimize formulations of recycled plastics and meet the needs of manufacturers more effectively. *'PLAST'lab will allow us to make greater strides towards improving the quality and quantity of recycled plastics…'* says Jean-Louis Chaussade. With the launch of PLAST'Lab, SUEZ aims at doubling its production of recycled plastics within 5 years.[157]

4.5.2 Strengthen the pull effect on the demand side through voluntary commitments

Stimulating or guaranteeing demand for recycled plastics could generate a 'pull' effect to accelerate the transition towards an effective after-use plastics economy. This pull effect could be policy driven (see section below) or industry driven. Voluntary commitments to use recycled content by (a group of) large (packaging) manufacturers or brand owners or an entire industry could create a significant pull effect. Some companies already have targets in place. By year-end 2016, PET material used for the plastic packaging of Philips products is slated to contain at least 25% recycled material in both mature and growth geographies.[158] Colgate has committed to using 50% recycled content in its packaging by 2020 and IKEA aims to use only recycled or bio-based plastics by 2020.[159]

4.5.3 Strengthen the pull effect on the demand side through policy

Several examples of measures by governments to increase such 'pull' can be found at all levels and across the globe. An entry-level measure is the use of public procurement rules to generate more demand for recycled materials: in Europe alone over 250,000 public authorities spend around 18% of GDP annually on public procurement.[160] Several countries have integrated strategic criteria in public tenders to increase demand and improve market conditions for recycled and recyclable plastics. In the Danish municipality Lolland, recycling and recyclability criteria for packaging have been included in their tender for cleaning services: 75% of material used for bags must be recycled or biodegradable; non-reusable packaging must be easy to separate into single material types; mono-materials are to be used if possible; only recyclable materials must be used; and use of dark colours must be avoided. Many similar examples of public procurement measures related to recycled materials can be found, for example, in the UK, Italy, France, Sweden, Norway, and the Netherlands.[161] Mandatory use of recycled materials is another example. In California, the Rigid Plastic Packaging Container Law, enacted in 1991, required producers of rigid containers to use at least 25% recycled content or meet one of the other compliance options such as source reduction, refillable packaging or reusable packaging.[162] This has significantly increased the use of recycled content in containers, and it has been a big boost to HDPE recycling nationwide.[163] Other examples are policy measures that aim to facilitate or incentivise the use of recycled materials. Some experts suggest also investigating options to abolish or adapt regulation that (unnecessarily) hinders recycling, such as Spain's lifting of the prohibition on using recycled plastic

for food packaging.[164] Incentives for the use of recycled content could include rebates on Extended Producer Responsibility (EPR) contributions, and other financial support mechanisms such as capital allowances or tax privileges.

4.6 EXPLORE THE ENABLING ROLE OF POLICY

Policymakers can play an important role in enabling businesses and local governments to overcome the barriers to increase the economics, quality, and uptake of recycling.[165] Different measures could be considered. Aside from the pull measures mentioned in the previous section, policymakers could also investigate policy measures such as (adaptive) EPR schemes, levies and/or bans on landfilling and incineration, and carbon or resource taxes. Such policy measures have not been the focus of this report, but would merit further investigation.

5 REUSE: UNLOCKING MATERIAL SAVINGS AND BEYOND

Reuse plays an important role as an 'inner loop' to enhance material productivity in a circular economy. In the case of plastics, it can create value in both business-to-business (B2B) and business-to-consumer (B2C) applications. In the B2B segment, different types of reuse systems, from those adopted by individual companies to shared-asset systems like the Physical Internet, can unlock significant value with benefits that go beyond direct material savings. By sharing standardised, reusable packaging, market participants are enabled to address structural waste in the logistics sector. In the B2C segment, adoption of reusable plastic packaging, and associated business opportunities, are driven by innovative user-centric models, by traditional and new reverse logistics systems and by policy and industry-led agreements.

5.1 REUSABLE PLASTIC PACKAGING IN B2B CAN UNLOCK SIGNIFICANT VALUE BEYOND MATERIAL SAVINGS

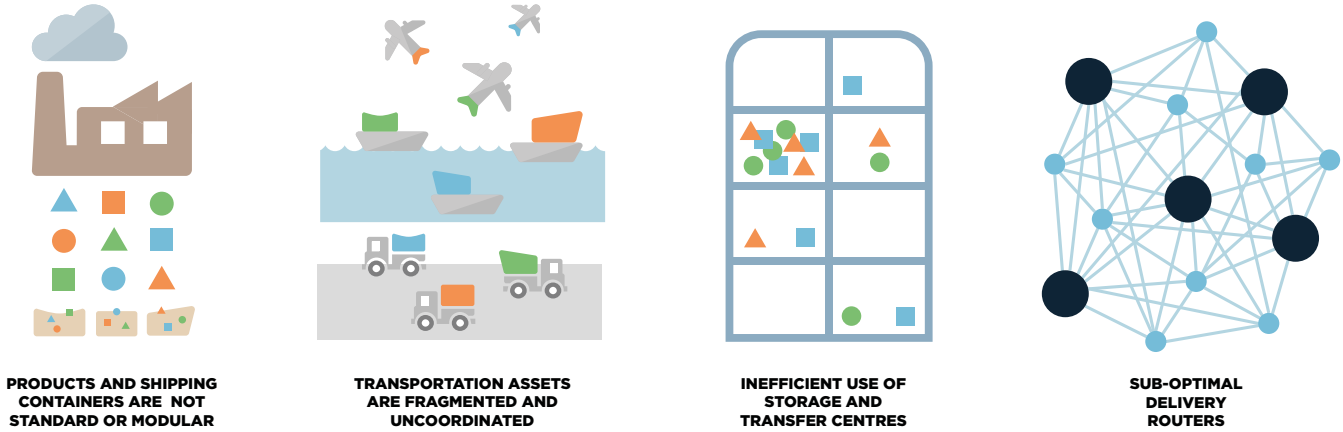
Adoption of reusable packaging in a B2B setting can clearly deliver substantial material savings versus the disposable alternative. It can also bring a range of further benefits, including reduced carbon footprint, less product damage, and optimised inventory management. In addition, if standardised, modularised, and ideally shared across companies, reusable packaging can serve as an enabler to address the structural waste in the logistics sector, and hence create significant value beyond packaging material savings alone. Characterised by the number and nature of participants, the different reuse systems range from individual adoption of reusable containers and reverse logistics to the Physical Internet — a logistics system based on standardised, modularised and reusable containers, using open networks across industries with pooled assets and protocols.

Reusable plastic packaging in B2B can create substantial material savings over single-use packaging. Even though manufacturing reusable packaging often requires more material per packaging unit than the single-use version, the amount of material required on a per trip basis is usually lower as the required volume is shared by the total number of lifetime trips. At UK supermarket Marks & Spencer, for example, each reusable plastic crate completes on average 300 trips before being repaired or recycled. Hence, while delivering the same or even better utility of transporting goods for a total number of trips, reusable packaging creates material savings versus single-use alternatives.

Beyond material savings, reusable plastic packaging in B2B could deliver a range of additional benefits including reduced carbon footprint, less product damage, easier product handling, and optimised inventory management. While the exact impact of reusing packaging on the carbon footprint depends on multiple factors such as manufacturing and recycling technologies, transportation distance, and vehicle utilisation, some studies have found that reusable plastic packaging performs better in this regard than disposable alternatives. For example, Sustain Limited calculated, using the PAS 2050 standard[166], that Schoeller Allibert's Maxinest tray, a standard reusable plastic crate for transporting fruit and vegetables, has a carbon footprint of 26 kg CO_2e per unit, much less than the 71 kg CO_2e per unit of standard cardboard boxes.[167] Due its sturdiness and potential for additional tools such as Radio Frequency Identification (RFID), reusable plastic packaging can result in less product damage, easier product handling and optimisation of inventory management. US tortilla manufacturer Mission Foods, for example, claims that adopting reusable plastic packaging with RFID across their supply chain enabled them to capture value worth USD 18 million over five years.[168]

In addition, reusable packaging in the B2B segment can serve as an enabler to address the structural waste in the logistics sector. As discussed in the report *Growth Within: A Circular Economy Vision for a Competitive Europe*[169], large and mature sectors such as mobility and the built environment have significant levels of embedded structural waste. The logistics sector is no exception. For example, in both the US and Europe 25% of all road-based freight trips are empty,[170] and of the non-empty trips only 60%[171] of space is utilised, resulting in a load factor of under 50%. In addition, the high cost of space in urban centres is forcing distribution centres further out, creating a demand for 'last mile' distribution networks that cause congestion and exacerbate system inefficiencies. Additional areas for improvement are shown in Figure 14. The total opportunity is substantial; based on the annual revenues of the European logistics sector, a 10–30% logistics efficiency gain would be worth USD 100–300 billion a year.[172]

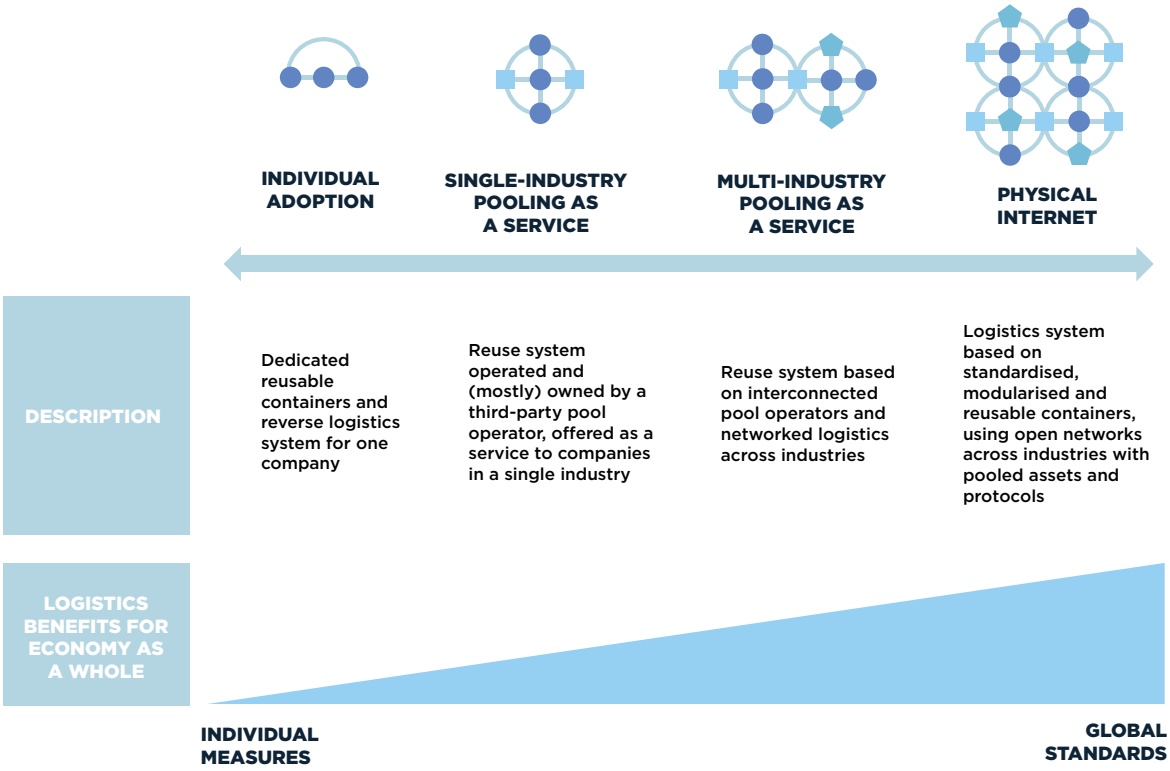
FIGURE 14: AREAS FOR IMPROVEMENT IN THE LOGISTICS SECTOR



Source: Adapted from original graphic featured in: Science magazine, *The Internet gets Physical,* (2014).

Reusable, modular and standardised plastic packaging can be an important enabler to address this structural waste in the logistics sector, and capture the corresponding economic opportunity — different models for the application of reuse systems are shown in Figure 15. While each of these models has specific benefits, and all have been implemented to some extent, reuse systems based on pooled packaging containers and shared distribution assets seem to hold the most potential.

FIGURE 15: REUSE SYSTEMS IN B2B PACKAGING

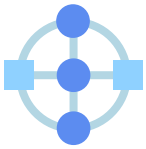


Source: Project MainStream analysis; Expert interviews.

INDIVIDUAL ADOPTION

Some retailers and brand owners have already implemented an individual system based on dedicated reusable containers and reverse logistics. For example, UK supermarket Marks & Spencer (M&S), operating across 850 stores in the UK, has the scale and distribution infrastructure to manage its own reusable packaging operation. M&S ships 98% of its products from supplier to store in reusable packaging crates. And, as it sells almost exclusively own-brand products, it has control over inventory from production to shelf. This example illustrates how control over a supply chain can lead to the successful implementation of standardised, reusable crates. Not every retailer is in such a

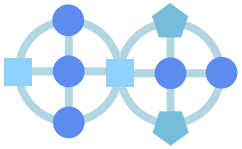
position but industry collaboration could allow other players to implement similar solutions, as demonstrated by the models below.



SINGLE-INDUSTRY POOLING AS A SERVICE

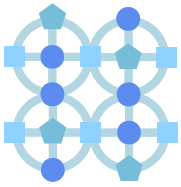
Driven by the cost savings available from standardisation, modularisation, and scale, some third-party operators organise a reuse system that offers reusable B2B packaging as a service to companies in a single industry. In Sweden, Svenska Retursystem operates such a pool of reusable packaging that services the whole retail sector — a model that, it claims, captures USD 18.7 million in savings and reduces waste by 50,000 tonnes annually.[173] This is the result of an industry-led collaboration. In 2001 the Grocery Manufacturers of Sweden (DLF), an industry organisation, and the trade association for grocery stores (SDH) launched a project to implement a reusable packaging solution across the food and grocery supply chain. Svenska Retursystem replaced a fragmented, inefficient model, which relied on single-use packaging and featured little or no collaboration between retailers.

Today, almost every perishable product for every grocery chain in Sweden is delivered in one of six types of standardised, reusable crates on a reusable plastic pallet. The supply chain includes the majority of Swedish food manufacturers, and roughly 200 additional food manufacturers throughout Europe that export their goods to Sweden. Since inception in 2001, nearly 1 billion crates have been delivered (replacing the same number of single-use packaging items) and the jointly owned operating company employs 135 people and operates four washing facilities across Sweden. Conny Swahn, Sales and Marketing Manager at Svenska Retursystem, explains that *'Today the (reusable packaging) system is a natural part of the supply chain within the Swedish grocery business. It is a model that could be replicated within any densely populated area with a high volume of products to move.'*[174]



MULTI-INDUSTRY POOLING AS A SERVICE

Some companies take the model of single-industry pooling as a service model a step further by connecting different industries, seizing opportunities for scale and standardisation. Brambles is one example of such a reusable packaging service company. It is active in more than 60 countries, has over 14,000 employees, and owns around 470 million pallets, crates, and containers that it operates in a network of 850 service centres. Thousands of companies use Brambles' assets within their supply chain as a pooled resource. The group operates in a variety of industries, with some overlap in container sizing and network protocols across sectors, while maintaining certain flexibility to meet specific sector demands. In the current model, the service centres and supporting logistics are also multi-industry. The key to further unlock multi-industry pooled reusable packaging lies in designing a container that offers modular sizing and flexible performance properties.



PHYSICAL INTERNET

Physical Internet is a vision of a new logistics paradigm based on systemic, creative thinking (see Figure 16). Its three fundamental principles are consistent with a circular economy:

- **Reuse:** Standardised, modular, reusable, recyclable containers.
- **Share:** Open networks with pooled assets and protocols.
- **Virtualise:** IT infrastructure that allows real-time tracking.

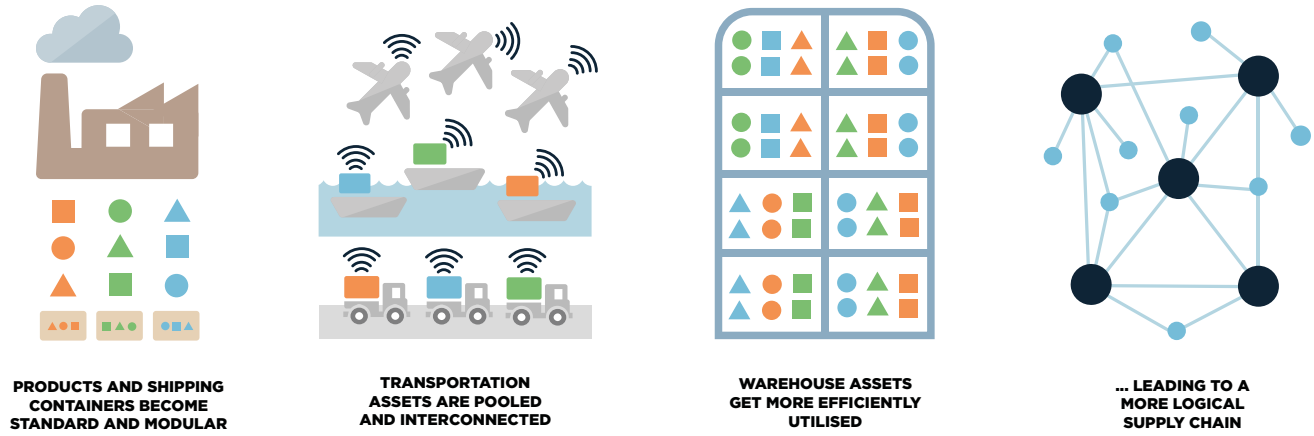
Box 7: Establishing global standards: The case of shipping containers

Standardised, modular, reusable packaging does not only create value in terms of packaging material savings, it is also the key to unlocking considerable value across the web of supply chains that govern today's material flows.

Global standards can provide the backbone to enable complex systems to scale up. Introduced by Malcom McLean in 1956, the standardised, stackable shipping container has been credited as the single-largest driver of globalisation. Before McLean's maiden voyage, it cost USD 5.86 and took just under an hour to load 1 tonne of cargo. Switching to the container system instantly cut this cost to USD 0.16 per tonne and by 1970 a container crew could load 30 tonnes per hour. Adoption was boosted by the United States' need to move vast quantities of material during the Vietnam war, and 20-foot and 40-foot containers have been the global standard since the 1980s.[175]

Container dimensions are not compatible with the way trucks are loaded and how goods are stored in warehouses, so the benefits of McLean's revolution have been limited to rail and sea. Further standardisation of B2B packaging formats would improve system effectiveness, across all modes of transportation. Emulating this idea — of modular packaging containers, standardised across all B2B packaging formats — is also the cornerstone of the concept of open, shared logistics networks known as the Physical Internet.

FIGURE 16: THE PHYSICAL INTERNET: A NEW LOGISTICS PARADIGM ENABLED BY REUSABLE AND STANDARDISED PACKAGING



Source: Adapted from original graphic featured in: Science magazine, *The Internet gets Physical,* (2014).

Unlike the conventional approach of owning and optimising *assets*, participants in the Physical Internet aim to optimise *delivery* of the product, using available assets regardless of ownership. The model operates like a light rail system in an urban centre; vehicles run at an adjustable frequency along designated routes with regular stops. Rather than every citizen owning her/his own vehicle and optimising her/his individual route, routes and stops are designed, and frequencies set, to optimise system effectiveness.

'With the Physical Internet, you [as a user] wouldn't care about the route. You care about the timeliness, the cost, and the quality of the service.'[176]

The Physical Internet model relies on a high number of shared hubs, connected by pooled transportation assets that carry modular, standardised, reusable containers from point of supply to point of purchase for multiple users. Intelligent asset technology within the container would allow each user to track their product's location and status in real-time without having to own the asset being utilised. Modular containers allow for efficient stacking and faster changeovers, meaning goods going to the same destination can be aggregated as they move through the supply chain.

Given the intelligent asset technology available today (e.g. tracking), a Physical Internet-type system seems a realistic prospect. For example, RFID tags already allow real time tracking of assets through the supply chain, and the combination of passive, battery-less chips in transport containers and active, powered, readers at various points in the supply chain, has enabled greater control of inventory movements. As outlined in the Ellen MacArthur Foundation's report *Intelligent Assets — Unlocking the circular economy potential*, the technology is expected to become more affordable and more accurate, enabling wide spread adoption.[177]

The Physical Internet offers significant opportunities — if adopted to service just 25% of the freight flows in the US, the resulting productivity gains would boost profits by USD 100 billion and cut CO_2 emissions generated by road-based freight by 33% (or 200 million tonnes) annually.[178] Specific modelling using data from French retailers Carrefour and Casino of 'non-fresh food' product flows and their most important 106 suppliers suggested a 20% reduction in kilometres covered, capturing economic benefits and reducing CO_2 emissions generated by the product flows by 60%.[179]

The Physical Internet is at pilot stage today. However, there is a clear foundation and growing awareness of the concept, with research and initial pilot projects in both the EU and US. Comprehensive academic research and modelling has been completed in three key areas: modular containers, optimal hub networks, and system protocols. In parallel, industry initiatives to improve effectiveness are being implemented across different markets and geographies. As logistics is a fragmented, globally integrated, mature market with a high degree of local optimisation, a joined-up approach will likely be needed to bring about a paradigm shift and to capture the full potential offered by the Physical Internet.

5.2 INNOVATIVE BUSINESSES COMPLEMENT TRADITIONAL MODELS TO CAPTURE VALUE IN B2C REUSABLE PLASTIC PACKAGING

Increased distance between point of supply and point of use, coupled with decreased costs of single-use packaging, has, in many parts of the world, led to a nearly complete disappearance of B2C reusable plastic packaging. However, a rise in innovative business models as well as a potential continuation in recent policy developments could put this model back on the map.

Innovative business models can capture value by capitalising on the willingness of users to reuse in the home. Traditional reusable packaging models (such as those for returnable glass bottles) have typically relied on reverse logistics to get the packaging back to the supplier to be washed and refilled. However, innovative models, where the responsibility for refilling takes place in the context of the household, are demonstrating how reusable B2C packaging can have success in different formats.

Splosh and Replenish are two businesses that have developed customer models based on different reusable packaging formats that enable a user to refill in the home. This model has the potential to reduce the volume and simplify the pallet of plastics used in packaging.

Replenish estimates that one of its reusable containers can replace up to 30 single-use equivalents.[180] By first providing reusable containers and afterwards just packaging the active ingredients in liquid 'refill pods' that fit into the initial consumer-sized bottles, the company believes that its format could replace any product that is largely water based. Replenish estimates that in America every year 42.1 billion containers are used for products that are 70–90% water.[181] By shipping just the active ingredient in concentrate form and assuming each container is reused in the home 30 times, the same value and convenience can be delivered with significantly reduced levels of packaging, estimated to be 341,000 tonnes of plastic packaging per annum in the United States alone.[182]

Once a user invests in the home refill system, concentrate pods are purchased online, digitalising the brand. As a result, there is reduced emphasis on primary packaging to provide brand value. This could have the effect of simplifying the pallet of plastics used versus traditional physical retail formats. For example, some multilayer packaging formats used today include an outer layer with the sole purpose of creating a clean finish for printing inks.

Replenish believes the growth in penetration of online shopping presents reuse opportunities. As more fast-moving consumer goods are purchased online there will be an increased demand for e-commerce-friendly streams of packaging. Big businesses are already responding to this trend, for example Coca-Cola Enterprises recently announced a pod-based home refill system.[183]

User-centred reusable packaging is also emerging in the high street retail environment. Packaging in bulk, in store is in certain cases becoming associated with quality as high-end grocery stores in developed markets look to reinforce the message of small-batch, local sourcing. Planet Organic, a high-end organic food retailer based in the UK, has recently adopted this model by launching the 'Unpackaged' concept in one of its stores.[184] Shoppers are encouraged to bring their own containers and use self-service weighing machines to buy what they need from an extensive range of fresh and dried grocery products.

Rising packaging costs, improved product technologies, and faster distribution networks will likely boost adoption of innovative models. The relative cost of packaging is rising for some segments — in the United States the cost of fresh produce packaging is expected to grow 32% by 2024, while in the same period fresh produce production will grow only 2% as packaging takes on a greater role in the protection, traceability, and marketing of fresh fruits and vegetables.[185] As the costs of packaging and associated logistics contribute a greater share of the cost of goods sold (COGS), reusable packaging formats could unlock economic advantage.

Reuse models reliant on traditional reverse logistics, which have proven to work for non-plastic applications such as glass bottles, could become increasingly relevant for plastic packaging, especially given current trends in logistics, retail and e-commerce. Increased distance between point of supply and point of use has, in many parts of the world, led to a nearly complete disappearance of B2C reusable packaging reliant on reverse logistics. However, under the right conditions, reverse logistics models for packaging formats that include the end user can be commercially successful, as is demonstrated by glass beverage containers. In both developed and developing markets, deposit systems for glass bottles exist that effectively incentivise container return. These models succeed when (i) distances between point of supply and point of use are kept short, for example around a growing number of micro-breweries with a largely local customer base, or in the case of Belgian retailer Delhaize, which imports its best-selling wines in bulk and bottles them close to its local market in reusable bottles, or (ii) where the set-up cost of a reverse logistics system acts as barrier to entry for new entrants.

Commercially successful examples of reverse logistics models exist at scale: 47% of SABMiller's current global business is in refillable bottles,[186] and Coca-Cola is typically able to cycle its glass bottles 35–45 times.[187] Typically a combination of factors

make reverse logistics systems viable: a high cost of raw materials relative to other input costs, low cost collection and distribution infrastructure (often the result of efficient back-hauling in developed economies or low-cost labour in developing economies), low bargaining power of retailers, and relatively undifferentiated packaging types. This is covered in greater detail in the Ellen MacArthur Foundation's report *Towards a Circular Economy — Opportunities for the consumer goods sector*.[188]

A new paradigm for B2B logistics, such as the Physical Internet, could catalyse systemic change for the B2C segment. Currently, reverse logistics models that include the user seem viable only for mostly high-value applications like glass. The Nespresso coffee pod delivery and collection system is another example of a B2C reverse logistics operation; it relies on a high-value product with high-value aluminium packaging. A new system based on shared logistics assets could help reduce the cost barrier attached to reverse logistics models by creating an open infrastructure for new business models to utilise. In such a system, the modular dimensions that define B2B shipments would set the boundary conditions for standardisation of primary product packaging.

Now is the time to act as divergent trends affecting the point of supply and point of purchase are straining the existing logistics infrastructure. The growth of e-commerce and the increasing numbers of people living in urban centres is forcing a greater disaggregation of products into the current logistics system, leading to congestion challenges in urban environments. The world's top ten online grocery markets are forecast to double in size by 2020, and more retailers are moving to capitalise on this growth.[189] Amazon's PrimeNow[190] and Dash Button[191] services (already available in the United States and the UK) offer a glimpse of what is to come with one-hour delivery of everyday items such as cold beer, and auto-replenish of household essentials, respectively. It is yet unclear how these trends will affect B2C packaging in the long term, but if reuse models provide an effective solution for some of the associated challenges, then B2C reusable packaging could become increasingly relevant.

Offline, groceries are returning to the high street, occupying smaller spaces closer to residential areas with localised stores that stock a range of products tailored to the local demographic. The evolution of high-frequency, small-basket transactions means the idea of one large 'weekend' grocery shopping trip is fading, and the megastore distribution model with a large-scale, long-haul, hub-and-spoke network may no longer be fit for purpose everywhere.

Box 8: Mumbai tiffin boxes

In Mumbai, India, a popular lunch-box delivery system offers a neat analogy for how the Physical Internet could work at the user level. Every day, over 200,000 dabbas (a standardised lunch box also known as the tiffin box), each containing a freshly cooked lunch, make their way across the complex maze of city streets and alleys to reach their end consumers. In a setting that combines high population density, limited infrastructure, congestion, and a largely illiterate workforce, the tiffin system thrives thanks to its historically evolved routing code of coloured shapes, numbers, and letters that designate the direction of travel at each hub.

A collecting dabbawala or box carrier, usually on bicycle, collects dabbas either from a worker's home or from a supplier. The dabbawala then takes them to a sorting place, where the boxes are sorted into groups. The grouped boxes are put onto coaches of trains and unloaded at stations according to the code, which also directs the local dabbawala to the point of delivery. The empty boxes are collected after lunch or the next day and returned to the respective point of origin with a high degree of accuracy — the unsubstantiated claim is that dabbawalas make less than one mistake in every six million deliveries.[192]

Policy and industry-led agreements are another lever that could have a significant impact on the potential of reusable plastic packaging in the B2C segment. One example is the effort to discourage single-use plastic carrier bags, favouring reusable or non-plastic alternatives. In 2015, a new European Directive came into force requiring member states to reduce the use of lightweight plastic carrier bags by taking measures that either reduce the per capita consumption, or restrict retailers from distributing them free of charge.[193] Policy in this area has been evolving over time; Bangladesh already banned disposable plastic bags in 2002 after they were found to have choked the drainage system during devastating floods.[194] Today, multiple countries around the world have some type of ban or tax on single-use plastic bags. Also measures for beverages bottles demonstrate how policy can drive adoption of B2C reuse models, away from the single-use alternative. In San Francisco, for example, the sale and free distribution of drinking water in single-use bottles of 21 ounces or less is prohibited on city property. At the same time, the legislation commits the city to install more widespread drinking fountains and bottle filling stations.[195] Similar measures are taken in several municipalities and campuses around the world.

In addition to policy, industry itself can drive adoption of reuse systems. In France, for example, a voluntary agreement signed by hypermarket chains reduced the number of single-use bags from 10.5 billion in 2002 to 700 million in 2013.[196]

6 COMPOSTABLE PACKAGING: RETURNING NUTRIENTS TO THE SOIL FOR TARGETED PACKAGING APPLICATIONS

For targeted applications, compostable plastic packaging — if coupled with the appropriate collection and recovery infrastructure — can help return nutrients of the packaged content (e.g. food) to the soil. Today, most plastics are designed to be either recyclable or compostable or neither of the two. Keeping both options open by design is usually not possible with current materials technology and after-use infrastructure. While designing packaging for recycling comes with the advantage of keeping material value in the economy, designing packaging for composting can be valuable for targeted applications: it offers a mechanism to return biological nutrients from the contents of the packaging that would have otherwise been lost, such as the residue of packaged food, back to the soil in the form of fertiliser. Successful initiatives have demonstrated the potential of compostable packaging at scale.

6.1 WHAT IS COMPOSTABLE PACKAGING?

The term 'compostable packaging' will be used in preference to 'biodegradable packaging' in this report, since both industrially compostable and home compostable materials are clearly defined whereas the term biodegradable packaging is very broad and not informative (see Appendix B).[197]

The definitions[198] for industrially compostable materials differ slightly across regions (EN13432 for Europe, ASTM D400 and D6868 for the US). A material is in essence **industrially compostable** if it meets the following four criteria:

- **Chemical characteristics:** it contains at least 50% organic matter (based on dry weight) and does not exceed a given concentration for some heavy metals.
- **Biodegradation:** it biodegrades by at least 90% (by weight) within six months under controlled composting conditions (temperature of 58 +/- 2°C).
- **Disintegration:** it fragments into pieces smaller than 2 mm under controlled composting conditions within 12 weeks.
- **Ecotoxicity:** the compost obtained at the end of the process does not cause any negative effects (which could be measured, for example, by the effect on germination and growth of plants).

Home compostable materials are always also industrially compostable. However, in contrast to industrially compostable materials, home compostable materials can be treated at ambient temperatures and the timeframes for biodegradation and disintegration can be longer. Moreover, parameters such as moisture content, aeration, pH, and carbon to nitrogen ratio do not need to be controlled.

Since industrially compostable plastics are only compostable under certain conditions and citizens might mistake loosely defined 'compostable' items as home compostable, it is important that materials are clearly labelled. Certification bodies (e.g. Vinçotte and Din Certo in Europe, BPI in the US) offer testing and certification services, and issue logos with product-specific coding to ensure traceability and transparency. Each certification body produces its own labels which, though referring to the same norms, can be confusing for citizens. The European Commission will implement (by May 2017) an act to ensure EU-wide recognition of compostable plastic carrier bags and provide citizens with information about their properties.[199]

Box 9: Bio-based, 'biodegradable' and compostable plastics are not the same

The term 'bioplastics' is often loosely used to refer to plastics that are bio-based, biodegradable, or both.[200] A material's origin and the available after-use options need to be clearly distinguished. In addition, as outlined above this report gives preference to the term 'compostable' over 'biodegradable'.

The term 'bio-based' describes a material's origin — i.e. wholly or partly derived from biomass[201] resources.[202] Renewably sourced materials (bio-based and greenhouse gas-based materials) are further detailed in Chapter 10.

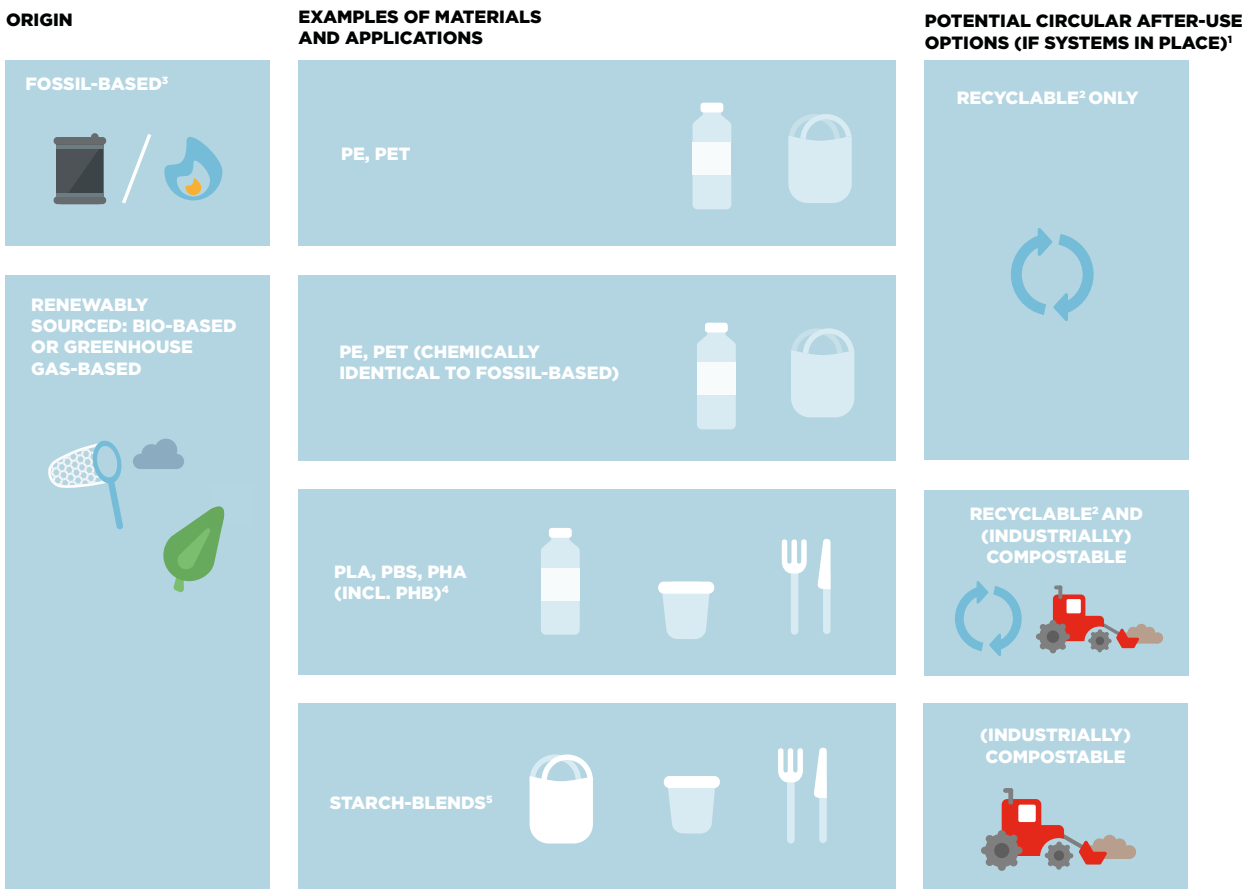
The term 'compostable' describes a material's *after-use option* — i.e. that a material is suitable for the

after-use pathway of home composting or industrial composting and fulfils the officially defined criteria for the respective environment. The term 'biodegradable' itself describes only that a material can biodegrade into natural elements with the help of micro-organisms (see Appendix B).[203]

Bio-based plastics are not necessarily compostable, as shown in Figure 17. Some bio-based plastics are designed for the technical cycle (bio-PET is recyclable) and some for the biological cycle (PLA is industrially compostable). Some bio-based plastics, such as PLA and PHA, are technically both recyclable and industrially compostable, if the right infrastructure is in place.[204]

Similarly, not only bio-based materials are compostable. Besides greenhouse gas-based plastics, also certain fossil-based plastics such as PBAT and BASF EcoFlex are industrially compostable. However, as such fossil-based compostable plastics represent a smaller segment of the market, they are not represented in Figure 17.

FIGURE 17: PLASTIC SOURCES AND CIRCULAR AFTER-USE PATHWAYS



1 Pathways shown are theoretical (technical) possibilities. Actual recyclability and compostability depends on after-use infrastructure in place. Incineration/energy recovery and landfill pathways not shown (possible with all plastics). Home composting not shown either (limited uptake today)

2 'Recyclable' is used here as short-hand for 'mechanically recyclable'. The alternative, chemical recycling, is not applied at scale today and has – with today's technologies – typically significant economic and environmental limitations

3 Some fossil-based plastics are industrially compostable (e.g. PBAT, BASF EcoFlex). They are not represented on this chart since they are not used at scale

4 All thermoplastics can theoretically be melted and recycled; though, in practice, only PLA is recycled in small volumes

5 Starch-blends cannot be recycled because of the variety of compositions of the blends

Source: European Bioplastics, *Fact sheet: What are bioplastics* (2015); Expert interviews.

6.2 COMPOSTABLE PACKAGING CAN HELP RETURN NUTRIENTS TO THE SOIL

The most promising applications for compostable packaging fulfil two criteria. First, the packaging is prone to be mixed with organic contents such as food after use. Making packaging compostable for such applications helps to return additional nutrients to the soil. Second, the packaging follows controlled material flows and does not typically end up in plastics recycling streams since compostable packaging can interfere with recycling processes with current material technology and after-use infrastructure. Examples of applications fulfilling both criteria are bags for organic waste; packaging

in closed-loop systems such as events, fast food restaurants and canteens; and packaging items such as teabags or coffee capsules.

6.2.1 Compostable packaging can help return organic nutrients to the soil in applications that are prone to be mixed with organic contents after use

In the circular economy, nutrients are kept at the highest utility at all times in both the technical and biological cycles.[205] Circular systems encourage biological nutrients to re-enter the biosphere safely for decomposition to regenerate the soil and become valuable feedstock for a new cycle. With increasing agricultural production and utilisation of soils, returning biological nutrients back to the soil becomes even more important.

Compostable packaging can be an important enabler to return more nutrients of packaged contents to the soil. While plastic packaging itself contains little nutrients, the packaged contents often contain valuable organic nutrients. This is particularly the case for food packaging. In certain applications, food might be difficult to separate from the packaging by default such as in coffee capsules and teabags.[206] Other applications are prone to a high food waste-to-packaging ratio after use (e.g. take-away packaging; food packaging at events, fast food restaurants and canteens).

Today, such biological nutrients are mostly landfilled or burnt together with the packaging. According to the Food and Agriculture Organisation of the United Nations, roughly one third of the food produced globally is lost or wasted.[207] A large share of this food waste is not returned to the soil. In the UK, for example, only 1.6 million tonnes of 14 million tonnes of food waste is captured and returned to the soil through anaerobic digestion every year.[208] In Australia, 47% of organic waste that is 'readily biodegradable' is landfilled and another 9% is sent to energy recovery.[209] In the US, uneaten food in landfills is the largest component of municipal solid waste.[210] In Europe, the average citizen generates 76 kg of food waste at home and an additional 34 kg outside the household[211] (e.g. in restaurants, catering services, and retail stores) not considering the 70 kg of waste per capita that is generated at the manufacturing level.[212] Even if only a fraction of this food waste could be returned to the soil through compostable packaging, this would make a big difference.

Compostable bags are one application that has been proven to be effective in increasing the amount of food waste returned to the soil. Compostable bags can be an important enabler in the collection of food waste from households and reduce the risk that non-compostable plastic bags find their way to industrial composting and anaerobic digestion facilities. Initiatives such as that in Milan (see Box 10) have proven that both the amount of food waste collected separately and the quality of the finished compost can be increased significantly with the help of compostable bags. Minimum compost quality levels for general use, including a maximum level of physical contamination for compost, are specified by bodies including The British Standards Institution and WRAP.[213] A study carried out by CIC (Italian Composting and Biogas Association) indicates that if collection at households is carried out with non-compostable PE bags, the expected content of non-compostable materials amounts to 9% of the input whereas it can drop to 1.4% with compostable plastic bags.[214]

Box 10: The successful use of industrially compostable bags in Milan

An initiative carried out in Milan illustrates the impact of an effort coordinated along the value chain and the use of industrially compostable bags on the quantity of nutrients that can be returned to the soil. In 2011, Milan had a separated food waste collection of 28 kg per inhabitant per year, resulting in a food waste collection rate of 19%.[215] Food waste in Milan was only collected from commercial sources such as restaurants, supermarkets, hotels, and schools. Food waste from private households was not collected and most of it could not be home composted since 80% of Milan's inhabitants live in high-rise buildings with no outside space.

As part of a project to increase the food waste collection rate, households were equipped with a vented bin with compostable plastic bags made with Novamont's Mater-Bi material. People could then purchase further compostable bags or use compostable shopping bags from supermarkets. In order to promote the adoption of industrially compostable plastic bags, single-use non-compostable plastic bags were banned.

The project has been successful and raised the separated food waste collection per inhabitant per year to 95 kg, more than tripling the collection of food waste.[216] The average content of non-compostable materials has been around 4% and has decreased over time, allowing the production of a compost of good quality for farmers through industrial composting and anaerobic digestion.[217]

6.2.2 Streams of compostable and recyclable materials need to follow separate pathways after use

Given that compostable plastics can interfere with today's recycling systems of other plastics like PE,[218] and that plastics that are not industrially compostable can contaminate the finished compost, contamination between compostable and recyclable after-use plastic streams should be avoided. Hence, compostable packaging is more suitable in controlled or closed environments where the risk of contamination is low. While critical today, as certain plastics are both (technically) recyclable and compostable, this constraint might become less relevant as time progresses. While non-compostable plastics could potentially be separated from food waste, this can cost up to around EUR 30 per tonne (at 9% contamination),[219] representing more than half of the gate fee received by operators of anaerobic digestion facilities and hence affecting the economics.[220]

6.2.3 Appropriate industrial composting and anaerobic digestion infrastructure needs to be in place

After collection, compostable packaging and the biological nutrients from the packaged content can be brought back to the soil through anaerobic digestion (AD) and/or composting processes. For home compostable materials, there is the additional pathway of home composting.

The main difference between anaerobic digestion and the industrial composting process is that the former occurs in the absence of oxygen. As a result, the anaerobic digestion process yields biogas in addition to the digestate that can be used as fertiliser.[221] This biogas can be used for renewable power production either in the form of electricity and heat (combined heat and power, CHP) or — if upgraded and refined — in the form of natural gas that can be exported to the grid (biogas to grid, BtG).[222] In the case of CHP, the heat and electricity produced can be used internally and the electricity surplus can be sold and exported to the grid. One tonne of food waste (at 60% moisture) produces typically 300–500 tonnes of biogas (with methane concentration around 60%) and hence produces 1,260 kWh. An average AD plant (with capacity of 750 kWe) can produce electricity for approximately 2,500 households (assuming 2,700 kWh per household).[223]

The anaerobic digestion process is often combined with an industrial composting post-treatment step. Such a post-treatment composting step allows stabilisation of the digestate and further biodegradation of any industrially compostable plastics, such as PLA, that might still be present in the digestate. Some countries, such as the UK and Sweden,[224] are exceptions to this procedure and the digestate is directly applied to the soil. Depending on the quality of the material streams and the source separation, industrial composting and anaerobic digestion processes require a pre-treatment step to extract items that do not biodegrade.

In the recent past, anaerobic digestion capacity has increased rapidly. The number of plants in Europe, for example, has increased from 3 in 1990 to 290 in 2015 with a combined capacity of 9 million tonnes per year.[225] With improvements in the biogas yield, biogas production and electrical power equivalents have grown at an even faster pace (up to twice as fast).[226] Further information on the anaerobic digestion process can be found in Appendix C.

For home compostable materials, there is a complementary third avenue: they can be treated in home composting environments. However, there are caveats. First, home composting is only beneficial if the sorting of home compostable materials and industrially compostable materials by citizens is supported by a clear distinction and intuitive labelling of the two material streams. Second, appropriate home composting infrastructure might not be available, for example, in urban areas. Home composting is only helpful in returning biological nutrients to the soil if the home composting conditions allow for full degradation and the finished compost finds a use. In addition, designing packaging to be home compostable — while fulfilling all packaging performance requirements — poses an innovation challenge for many applications. Since composting conditions in industrial facilities are controlled and more 'favourable' for the degradation process, more materials are industrially compostable than home compostable. Last but not least, a higher share of home compostable packaging does not mean that collection and recovery infrastructure is not necessary. Unless all materials in a region would be home compostable (which is highly unlikely), collection and recovery infrastructure would remain required.

6.3 SUCCESSFUL INITIATIVES HAVE DEMONSTRATED THE POTENTIAL OF COMPOSTABLE PACKAGING AT SCALE

The London Olympics, the city of Milan, the CoRR[227] effort in New York, and events in stadiums in the US[228] have proven the viability of anaerobic digestion and composting food waste along with industrially compostable packaging at large scale (several million end users). These initiatives have shown integrated value chains, from individuals to material management companies and farmers using the fertiliser. Lessons learnt from these initiatives have been well documented[229] and can be leveraged to further optimise processes and scale up the implementation of these initiatives. The main take-away is that stakeholders along the value chain need to fully buy into the vision and understand their role within the project (this includes citizens who need to be informed about how to sort food waste and packaging). This alignment can be ensured by, amongst others, (financial) incentives to foster cooperation (e.g. based on collection targets between composters and event organisers), or, in the documented cases, synchronisation was facilitated by local authorities providing a supporting policy framework (e.g. in the Milan case a ban on single-use plastic bags). Further scale-up of industrially compostable packaging could build on the lessons learnt from these successful initiatives.

PART III DRASTICALLY REDUCING LEAKAGE OF PLASTICS INTO NATURAL SYSTEMS AND MINIMISING OTHER EXTERNALITIES

7 DRASTICALLY REDUCING LEAKAGE INTO NATURAL SYSTEMS AND ASSOCIATED NEGATIVE IMPACTS

Today, an estimated 32% of plastics and plastic packaging escapes the collection system globally, generating high costs by reducing the productivity of vital natural systems such as the ocean and clogging urban infrastructure. The report *Valuing Plastic* conservatively estimates the costs of the negative externalities of plastics in the ocean — just one of the 'sinks' for leaked plastics — to USD 13 billion. Achieving a drastic reduction in leakage would require coordinated efforts along three dimensions: first, improving after-use infrastructure in high-leakage countries, an urgently needed short-term measure. Second, increasing the economic attractiveness of keeping the materials in the system. Third, reducing the negative effects of any likely remaining leakage by steering innovation towards truly 'bio-benign' materials, which represents an ambitious innovation challenge.

An estimated 32% of plastics escape the collection system globally.[230] Plastic packaging is particularly prone to leakage due to its small size, high rate of dispersion and low residual value. Today, at least 8 million tonnes of plastics (of which estimates suggest that plastic packaging represents the majority) leak into the ocean — just one of the 'sinks' for leaked plastics — every year.[231] Plastics that leak into oceans and other natural systems remain there for centuries resulting in high economic costs and causing harm to natural systems. While the total economic impact is still unclear, initial studies suggest that it is at least in the billions of dollars. The report *Valuing Plastic* conservatively estimates the costs of the negative externalities of plastics in the oceans to be at least USD 13 billion.[232] The Asia-Pacific Economic Cooperation (APEC) estimates that the cost of ocean plastics to the tourism, fishing and shipping industries was USD 1.3 billion in that region alone.[233] Even in Europe, where leakage is relatively limited, potential costs for coastal and beach cleaning alone could reach EUR 630 million (USD 695 million) per year.[234] Leaked plastics can also degrade other natural systems, such as forests and waterways, and induce direct economic costs by clogging sewers and other urban infrastructure. The economic costs of these impacts need further assessment. In addition to the direct economic costs, there are potential adverse impacts on human livelihoods and health, food chains and other essential economic and societal systems. The negative externalities also include entanglement and ingestion of plastics by various species. According to STAP, 'more than 260 species are already known to be affected by plastic debris through entanglement or ingestion'.[235] Plastics in oceans may also contain — or may act as a sponge for — a range of substances including some which raise concerns about potentially negative effects. The extent of the potential impact of substances of concern on the marine biosphere is not yet fully understood by the scientific community, which indicates a need for more research (see Chapter 8) and, where relevant, precautionary measures.

7.1 IMPROVE AFTER-USE COLLECTION, STORAGE AND REPROCESSING INFRASTRUCTURE IN HIGH-LEAKAGE COUNTRIES

A critical first step in addressing leakage would be to urgently improve after-use infrastructure in high-leakage countries. However, this measure in isolation is likely not sufficient. As discussed in the Ocean Conservancy's 2015 report Stemming the Tide, even under the very best current scenarios for improving infrastructure, such measures would stabilise, not eliminate, leakage into the ocean.[236] The expected reduction of global leakage (45% by 2025 in a best-case scenario) would be neutralised by the annual growth of plastics production of currently around 5%. As a consequence of such stabilised leakage, the cumulative total volume of plastics in the ocean would continue to rise quickly. Hence, ensuring that plastics do not escape collection and reprocessing systems and end up in the ocean or other natural systems requires a coordinated effort on multiple fronts. While other initiatives are addressing the important issue of improving after-use collection and reprocessing infrastructure, this report focuses on the complementary actions required.

7.2 INCREASE THE ECONOMIC ATTRACTIVENESS OF KEEPING MATERIALS IN THE SYSTEM

As described in Parts I and II of this report, creating an effective after-use plastics economy would contribute to a root-cause solution to leakage. Improved economics make the build-up of after-use collection and reprocessing infrastructure economically more attractive. Increasing the value of after-use plastic packaging reduces the likelihood that it escapes the collection system, especially in countries with an informal waste sector. In addition, dematerialisation and reuse are levers to 'do more with less plastics' and hold the potential to reduce leakage proportionally with the amount of plastics put on the market.

7.3 STEER INNOVATION INVESTMENT TOWARDS CREATING MATERIALS AND FORMATS THAT REDUCE THE NEGATIVE ENVIRONMENTAL IMPACT OF PLASTIC PACKAGING LEAKAGE

Today's plastic packaging offers great functional benefits, but has an inherent design failure: its intended useful life is typically less than one year; however, the material persists for centuries and can be damaging if it leaks outside collection systems.

Although the efforts described above could significantly reduce leakage of plastics into natural systems, it is doubtful that such leakage will ever be fully eliminated. Even in regions with advanced collection infrastructure, such as the US and Europe, 5% of plastics still escape the collection system, with plastic packaging particularly prone to leakage. [237] Even in the case that leakage of plastic packaging could be reduced globally from 32% to 1%, about 1 million tonnes of plastic packaging would still escape collection systems and accumulate in natural systems each year.

Therefore, there is a need for innovation towards truly bio-benign materials that address this design failure. Such materials would avoid harm to natural systems in case they escape collection systems. Like leaves that have fallen from a tree or a banana peel that has been separated from its packaged content — the banana — such bio-benign materials would safely and completely degrade after their useful life. For most applications, bio-benign packaging would still primarily be designed for recycling (with the exception of, for example, packaging that is designed for industrial composting as described in Chapter 6). However, its bio-benign characteristic would reduce the negative effects on natural systems in the unintended case of leakage. Paper offers inspiration — a widely used and recycled packaging material that is relatively benign if leaked into natural systems (unless it contains substances of concern such as certain inks).

Different avenues might help reduce the harm of (unintentionally) leaked plastics. Advanced biodegradability in freshwater and/or marine environments, a material palette without substances of concern, avoidance of colours and shapes that are typically ingested or otherwise harmful to marine life for applications with high risks of leakage, and radically new smart/ triggered processes that imitate metabolising processes in nature could all contribute to making materials benign to natural systems. Further research is required to identify the most promising avenues towards truly bio-benign plastics.

Today's biodegradable plastics do not measure up. As UNEP points out in a recent report, even plastics that are 'marketed as biodegradable' (i.e. plastics that are industrially or home compostable) do not 'provide a solution to the environmental impacts caused by marine litter'.[238] Indeed, industrially or home compostable plastics marketed as 'biodegradable' are not necessarily benign in the case of leakage into natural systems. Additive-mediated fragmentation in its current reincarnation has also not led to a breakthrough. Current 'oxo-degradable' (or rather 'oxo-fragmentable') plastics (as further explained in Appendix B) have not been proven truly benign, but rather have mostly led to fragmentation — increasing the quantity of microplastics in the ocean.[239]

Given the scale and importance of the ocean plastics issue, marine degradability is an important step in reducing the harm of plastics that escape the collection system. Marine degradable plastics are materials that, besides full biodegradation in a composting test, reach 20% biodegradation in a marine test within a period of six months, and at least 70% disintegration (i.e. smaller than 2 mm) in a marine environment within a period of three months.[240] An aquatic toxicity test is also required. No finished product has yet been approved as marine biodegradable. Plastic packaging made of

marine biodegradable material is not necessarily marine biodegradable itself. The shape of the product influences the biodegradation time, which is one of the criteria of marine biodegradability. The European Commission Joint Research Center approved two grades of the Mater-Bi (Novamont) for marine biodegradation[241] and Vinçotte has already approved one plastic material as marine biodegradable (PHA produced by MGH).[242] However, even certified marine degradable plastics (as defined by ASTM D 7081) might only limit some of the challenges and negative externalities. Some of the entanglement and ingestion issues, for example, would remain given the relatively long degradation timeline of three months. More research would be needed to assess the exact requirements.

Developing truly bio-benign plastic packaging represents a significant innovation challenge that will take time to overcome, particularly because such plastics would also need to be functional and cost-effective in order to be a viable alternative at scale.

8 SUBSTANCES OF CONCERN: CAPTURING VALUE WITH MATERIALS THAT ARE SAFE IN ALL PRODUCT PHASES

Besides polymers, plastics contain a broad range of other substances. Certain of these substances raise concerns about complex long-term exposure and compound effects on human health, as well as about their impact upon leakage into natural systems such as the ocean. While scientific evidence on the exact implications of substances of concern is not always conclusive, there are sufficient indications that warrant further research into and accelerated development and application of safe alternatives. These research and innovation efforts would need to be complemented with enhanced transparency on the material content of plastics and, where relevant, the application of the precautionary principle to phase out specific (sets of) substances raising concerns of acute negative effects. The concerns and potential upside for the industry and broader society associated with management of substances of concern are motivators for stakeholder action.

8.1 CERTAIN SUBSTANCES IN PLASTIC MATERIAL RAISE CONCERNS DUE TO POTENTIAL ADVERSE EFFECTS AND LIMITED TRANSPARENCY

Plastics are usually made from a polymer mixed with a complex blend of materials known as additives. These additives, which include flame retardants, plasticisers, pigments, fillers, and stabilisers, are used to improve the different properties of the plastic or to reduce its cost. There are thousands of additives on the market. Today, 13.2 million tonnes of additives are produced annually, and global demand is forecast to continue increasing in the coming years, at about 4.5% annually in terms of volume.[243] Global plasticiser consumption, for example, was about 6.4 million tonnes in 2011, and is expected to grow at a similar rate, with a majority of plasticisers being phthalates (70% in 2014).[244] While the exact additives used depends on the plastic type and its application, overall the plastic packaging industry uses various additives, (e.g. to reduce oxidation and to improve slip properties). Moreover, the packaging segment led the plastic additives market in 2013 and is projected to continue to be the largest market, with an annual growth of 4.7% between 2014 and 2019 in terms of volume.[245]

Multiple substances of concern are used in plastics — intended, such as through the use of polymer precursors and additives, and unintended ones like catalyst residues and unwanted compounds formed by side-reactions.[246] Their presence does not necessarily have a negative effect on human health or the environment as concentrations might be low or exposure to them may be limited.

Box 11: Substance of Concern (SoC)

In this report, chemical elements and their compounds are called substances of concern if they may have serious and often irreversible effects on human health or the environment. This concept involves risk associated with context and exposure, for which insights continue to evolve as the science progresses.

Concerns about hazards of substances are inherently related to risk, context, and exposure. Individually, certain substances may cause harm if concentrations or length of exposure exceed a certain threshold. Moreover, recent scientific research shows that, even in low concentrations, the combined effects from exposure to certain substances over a prolonged period of time may have adverse effects on human health and the environment.[247] Adverse effects include causing cancer, inducing mutations in an organism, or endocrine disruption, which means that substances mimic natural hormones in the body and thereby cause health problems such as diabetes and obesity. As our understanding of substances of concern is still evolving, it is only possible to consider the *currently* estimated hazards.[248]

Similar SoC concepts have been defined by regulations such as the European Commission's Registration, Evaluation, Authorisation, and Restriction of Chemical Substances (REACH), or the US Environmental Protection Agency-administered Toxic Substances Control Act. The European Chemicals Agency,[249] for example, uses REACH's definition of Substances of Very High Concern (SVHCs), i.e. substances with the following properties:

- Substances meeting the criteria for classification as carcinogenic, mutagenic or toxic for reproduction category 1A or 1B in accordance with Commission Regulation (EC) No 1272/2008 (CMR substances).
- Substances which are persistent, bio-accumulative and toxic (PBT) or very persistent and very bioaccumulative (vPvB) according to REACH (Annex XIII).
- Substances identified on a case-by-case basis, for which there is scientific evidence of probable serious effects that cause an equivalent level of concern as with CMR or PBT/vPvB substances.

Even though plastics are widely used in packaging and their content is often regulated, individuals, scientists, and NGOs have raised concerns regarding the effect of specific (classes of) substances in this context. While the science is not always conclusive, some studies have found evidence for possible adverse effects on human health and the environment in specific cases relating to substances of concern in plastic packaging.[250] The styrene monomer — a precursor to polystyrene and several copolymers — has been found to leach out of packaging into food (simulants).[251] Even if the migrated monomer concentration is low, concerns are raised because styrene is listed by the US National Research Council as 'reasonably anticipated to be a human carcinogen'.[252] Phthalates are another example as many are suspected to be toxic for reproduction and endocrine-disrupting, with emerging evidence linking them to two of the biggest public health threats facing society — diabetes and obesity.[253] Some policymakers have introduced measures to reduce children's exposure to phthalates, but they are still found in plastic packaging.[254] In Sweden, the government has directly addressed this issue by asking its chemicals agency to push for the use of phthalates to be phased out in the country. In dialogue with industry, the agency is proposing a variety of measures driving the substitution of the most harmful phthalates.[255] In a number of countries, concerns have been raised about regulatory frameworks, regarding knowledge gaps, range of substances or applications covered and enforcement of legislation.[256] REACH, for example, exempts stabilisers (substances added to preserve the stability of the polymer) from registration.[257]

Plastics applications may or may not be subject to specific regulations, as is the case for food packaging.[258] These regulations are not necessarily aligned between different product uses or (global) regions. This fragmented regulatory situation, combined with the complex plastics material landscape, increases the lack of transparency on plastics components. Within the broader plastics industry there are several examples of substances of concern causing issues, including risks of adverse effects on human health and the environment, and barriers to safely closing the plastics material loops. An example of the former issue is phthalates, which are most commonly used as a plasticiser in PVC. Because of their potential effect on human health, certain phthalates have been banned for use in children's toys in both the EU and US, impacting manufacturers, distributors, retailers, and importers.[259] An example of the latter issue is addressed in a resolution adopted by the European Parliament in 2015 on phthalates preventing recycling: *'The EU Commission should not authorise the recycling of plastics that contain the banned PVC softener diethylhexyl phthalate (DHEP), because it poses a reproductive toxicity threat to exposed workers and could render their male foetuses sterile.'*[260]

Brominated flame retardants (BFRs) are another example. Researchers, investigating the presence of a recycled polymer waste stream from waste electric and electronic equipment, have found these substances of concern in black plastics used in kitchen utensils.[261] According to a publication of the Cancer Prevention and Education Society, *'These BFRs have presumably been introduced via the plastic recycling process, as there would be no need for them in virgin monomers intended for this purpose, and they would be forbidden for use in articles intended for use in food preparation.'*[262]

8.2 A PALETTE OF MATERIALS WITHOUT SUBSTANCES OF CONCERN HELPS ENABLE SAFE AND EFFECTIVE PLASTIC PACKAGING MATERIAL CYCLES

Substances of concern can create issues when closing plastic packaging material loops — whether the plastic is recycled, composted, sent to energy recovery, or leaks into the environment. Avoiding substances of concern when designing plastics, and also other packaging components like inks and adhesives, with intended and unintended after-use pathways in mind, is therefore an important step towards rendering those pathways safe and effective (see Figure 18).

8.2.1 Effective biological after-use processes and reduced soil contamination risk

When closing the biological cycle, SoCs can cause problems for the initial after-use treatment process itself as well as for further product phases. The presence of heavy metals in packaging or packaging components can hinder composting as very high concentrations of, for example, lead or cadmium used in pigments can inhibit the bacterial

growth essential for the process. In addition, the presence of heavy metals in the final compost is highly detrimental to the quality of compost and leads to a reduction of the agronomic value because of its eco-toxicological effects on future plant growth.[263] The cultivation of food crops in contaminated soil could potentially allow SoCs to enter the food chain and pose a potential risk to human health.[264] *'Among the possible negative effects of compost utilisation, the potential release of toxic heavy metals into the environment and the transfer of these elements from the soil into the food chain generally are claimed as the most relevant.'*[265]

Governments and other standard-setting bodies aim to manage these possible negative effects with standards for plastics and packaging. So far standards covering biodegradation, disintegration, and impact on the process and the resulting compost have been introduced. Examples include the EU requirements for packaging recoverable through composting and biodegradation, and the International Organisation for Standardisation (ISO) specifications for compostable plastics. These contain criteria such as maximum levels for heavy metals. Product certification by a recognised, independent third party should guarantee that not only the plastic itself is compostable but also all other components of the product, e.g. colours, labels, inks, glues, and remnants of the content. Avoidance of SoCs in biodegradable plastic packaging and the associated components improves the composting process, reduces the risk of SoCs entering the food chain, and reduces costs of compliance with composting regulation.

8.2.2 Reduced risk of SoC contamination and concentration through recycling and improved yields and quality

Recycling has to deal with contamination from all stages of the plastic product life cycle — SoCs intentionally bound into the plastic as additives or precursors, residues from catalysts used during production, and a mix of unidentified substances from different sources in recycling streams. This SoC contamination could cause issues for the recycling pathway in different ways.

First, potentially harmful substances such as catalysts, additives, or components of inks and adhesives are not necessarily completely filtered out when packaging is recycled, depending on the efficiency of the decontamination stage of the recycling process.[266] Hence, they remain in the loop and can be transferred into newly manufactured goods. When this happens, the additives do not necessarily contribute to the intended characteristics of the new material and, worse, may in some cases pose a hazard to human health.[267] The FDA confirms this risk in an industry guidance: *'The possibility that chemical contaminants in plastic materials intended for recycling may remain in the recycled material and could migrate into the food the material contacts is one of the major considerations for the safe use of recycled plastics for food-contact applications.'*[268]

For example, brominated flame retardants, commonly used in plastics (such as (expanded) polystyrene and polypropylene), textiles, and electronic equipment, have been (or are scheduled to be) phased out via regulation or on a voluntary basis as they are associated with endocrine disruption, reproductive toxicity, and cancer.[269] However, some hazardous flame retardants are still found in food packaging and as this presence is possibly linked to plastics recycling, concerns remain.[270] Combined with limited transparency on substances in the mix of materials being recycled, contamination by SoCs could affect the (perceived) value of the recyclate. These concerns are conceptually similar to, for example, bisphenol A (BPA) issues in recycled paper.[271] Also, substances of concern could be released during the recycling process.[272]

Furthermore, events in other recycling loops (such as ink concentration in recycled paper and the associated de-inking processes) have led to concerns about the possible risks posed by the *concentration* of SoCs when recycling plastic packaging. As very little plastic packaging gets recycled in multiple closed loops today, there is still uncertainty about these risks over a longer period of time. Finally and coincidentally, some of the best-known materials linked to substances of concern also hinder recycling yields from a technical perspective, which provides another reason to design them out (see, for example, PVC in Chapter 4 on recycling for more detail).[273] Innovation towards plastic packaging without SoCs means that material loops can be closed safely and effectively. This view is reflected in a green paper on plastic waste by the European Commission: *'Reducing hazardous substances in plastics would increase their recyclability. Gradual phasing out of those substances in both new and recycled products would also reduce risks associated with their use.'*[274]

8.2.3 Reduced hazards, and potentially costs, posed by combustion

When burnt, plastic packaging can release or create substances of concern, including but not limited to the heavy metals contained in certain additives, acid gases, dioxins that are a product of incomplete combustion of chlorinated polymers, and other persistent organic pollutants that can significantly affect human health.[275] In addition, combustion creates ultrafine particles that are toxic regardless of the hazard potential of the original material.[276] These pollutants are identified by some policymakers, in the EU and United States for example, who have enforced limits on emissions. For all of these reasons, combustion with energy recovery requires extensive pollution controls. In advanced combustion plants, for example, ultrafine dust is addressed with filters capturing up to

99.99% of particles.[277] In several parts of the world, for example in China, pollution controls are not sufficiently robust resulting in growing concerns over the pollutant emissions.[278]

Even if advanced pollution filters are in place — through multiple systems for gas cleaning requiring additional investment and operating costs — it is still unclear how to characterise the hazards posed by the remaining particles emissions for human health and the environment, especially in comparison to alternative after-use treatments.[279] Moreover, waste incinerators generate ash that is contaminated with SoCs like heavy metals and persistent organic pollutants and that requires safe disposal.[280] According to the incinerator industry, most incinerators generate 1 tonne of ash for every 4 tonnes of waste burnt.[281] This includes smaller volumes of air-pollution-control (APC) residue and larger volumes of incinerator bottom ash (IBA). APC residue is considered hazardous waste according to European legislation and requires a suitable disposal method after treatment, with costs of EUR 20–250 per tonne of residue.[282] IBA could be recycled as a secondary aggregate in construction applications, subject to specific conditions and given further treatment — otherwise it should be disposed of in a suitable manner.[283]

8.2.4 Reduced serious hazards resulting from leakage into the environment

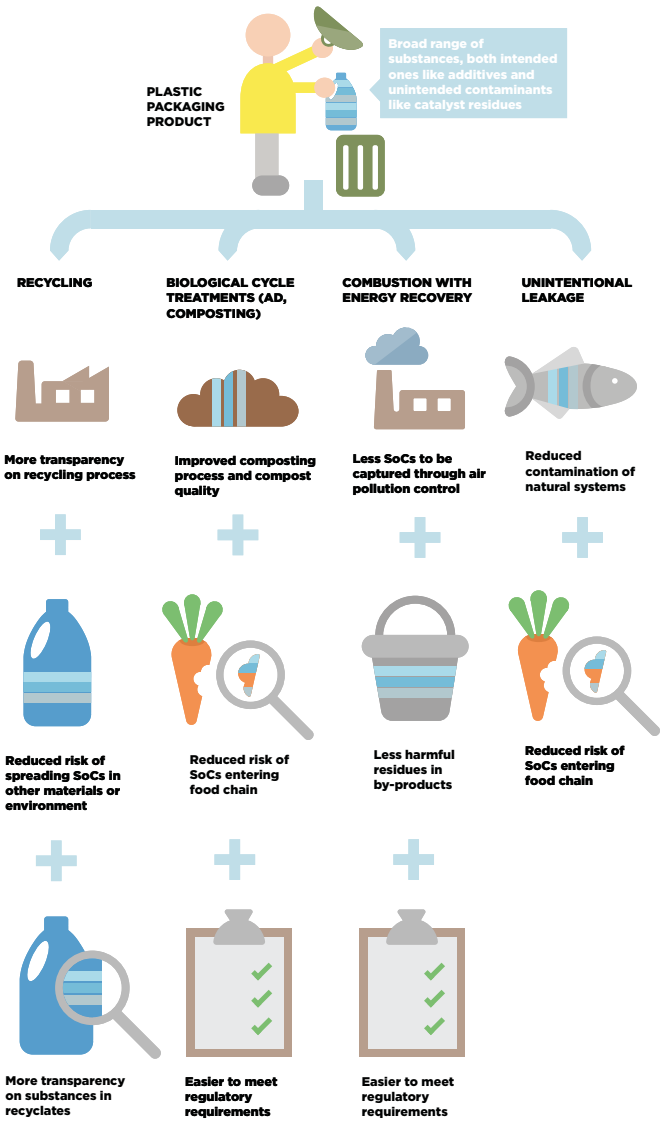
Leakage of plastic packaging creates various problems, as explained in Chapter 7. In addition to potential issues related to SoCs embedded within the plastic material, which is the focus of this chapter, two other concerns are often discussed. The first one is the physical presence of plastic packaging debris which can cause entanglement, digestion blockage, and suffocation.[284] The second one relates to microplastics, which can act like a sponge and attract hydrophobic substances of concern from the surrounding (marine) environment such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs), which subsequently could enter the food chain if ingested by marine animals.[285]

When considering SoCs embedded within plastic packaging, concerns are raised as monomers, additives, and non-intentionally added substances can leach out of plastics and the discharged leachate can introduce plastic-derived contaminants into the environment.[286] Examples include vinyl chloride, styrene, BPA, and certain phthalates, which all have adverse effects on human health and the environment.[287] When such SoCs are also hydrophobic, they can be stored in biological systems and theoretically bio-accumulate up the food chain.[288]

The 150 million tonnes of plastics currently in the ocean include approximately 23 million tonnes of additives.[289] While the speed at which these additives leach out of the plastic into the environment is still subject to debate, some estimates of this speed suggest that about 225,000 tonnes of such additives are released into the oceans annually. This could increase to 1.2 million tonnes per year by 2050.[290] Hence, the current situation suggests more research is needed to develop a comprehensive understanding of the risks associated with substances derived from (marine) plastics, including effects of complex long-term exposure and of combined substances, in addition to precautionary measures, where relevant.[291]

As discussed in Chapter 7, designing out substances of concern is a prerequisite for the development of bio-benign materials that safely decompose when (unintentionally) leaked, especially into the marine environment.

FIGURE 18: DESIGNING PLASTICS WITHOUT SUBSTANCES OF CONCERN HELPS ENABLE SAFE AND EFFECTIVE AFTER-USE PATHWAYS



Source: Project MainStream analysis; Expert interviews.

8.3 THE CONCERNS AND POTENTIAL UPSIDE ASSOCIATED WITH SOCS MANAGEMENT ARE MOTIVATORS FOR STAKEHOLDER ACTION

While scientific evidence on the exact implications of substances of concern is not always conclusive, some stakeholders are already taking action. They are motivated by different reasons — regulators are driven by the precautionary principle and potential cost to society, and businesses anticipate reputational risks and aim to capture potential economic value.

Given the possible impact on human health and the environment, some policymakers, academic institutions, and NGOs are raising concerns about SoCs. Regulators are also putting precautionary measures in place, even though the evidence is not yet conclusive on the potential impact of certain hazards. This is in line with what is called the precautionary principle:

'When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically. In this context the proponent of an activity, rather than the public, should bear the burden of proof. The process of applying the precautionary principle must be open, informed and democratic and must include potentially affected parties. It must also involve an examination of the full range of alternatives, including no action.'[292]

This principle has been prescribed in the Treaty of Lisbon (article 191) as a base for the European Union policy on the environment. It also now acts as a guiding principle in other domains and serves many different purposes for which international action is required, such as climate change.[293]

Some experts claim that in the absence of direct information regarding cause and effect, the precautionary principle is critical to enhancing reproductive and endocrine health.[294] Besides health concerns, a 2015 study concludes that exposure to endocrine-disrupting chemicals (including those found in plastics) in the European Union contributes substantially to disease and dysfunction, causing health and economic costs exceeding EUR 150 billion per year (an estimate that would have been even higher with a broader analysis).[295]

The concerns raised have also motivated companies to start taking measures in order to protect its own brands. For example, in 2015, the Danish retailer Coop Denmark stopped selling microwave popcorn as its packaging contained fluorinated substances, which are endocrine disruptors and have potentially adverse health effects. This followed an earlier phasing out of all fluorinated substances from its own brands in 2014.[296] Unilever committed to eliminating PVC from its packaging in 2009 given the concern around its disposal. By the end of 2012 virtually all Unilever packaging was free of PVC, which was replaced with alternative materials that provide the same functional properties as PVC at a viable cost.[297] After discovering issues with the migration of printing ink chemicals, the global food and beverage company Nestlé developed a guidance note on packaging inks, lacquers, coatings, and varnishes, specifying the substances that can be used in its packaging.[298] Nestlé then shared the document with vendors and upwards in the packaging value chain.

Seeking to preserve value at risk and even create growth, leading companies are introducing alternatives for SoCs. Ways to capture such economic value include anticipating changing customer demand, reducing or avoiding hazardous waste disposal costs, reducing compliance costs by being ahead of changing legislation, and de-risking the production process. For example, chemicals manufacturing company BASF reported in 2014 that it had doubled production capacity for its non-phthalate plasticiser Hexamoll DINCH to 200,000 tonnes per year at its Ludwigshafen site in Germany by opening a second plant. This decision aimed to satisfy growing customer demand for non-phthalate plasticisers and strengthen supply security worldwide, as explained by the president of BASF Petrochemicals: *'In the last few years we have been experiencing a strong customer demand for alternatives to traditional phthalates and a market change to non-phthalate plasticisers.'*[299]

Further actions to address concerns and capture potential upsides associated with SoCs include expanded research on their effects, enhanced transparency on plastics content, and continued development of harmless alternatives with similar or better functionality and costs. Continuing and expanding research is required to better understand the effect of substances of concern on human health and the environment in different use and after-use pathways, including leakage into the environment. Following the precautionary principle, this research should be complemented by enhancing transparency on the material content of plastics and plastic packaging as well as by focusing innovation on replacing substances of concern with harmless alternatives that have similar or even better functionality and costs. Substances for which acute toxicity during use in plastics has been proved, should be taken out of the current system and disposed of in a suitable manner. In this way human health is safeguarded, and an effective after-use economy is enabled by closing the material loops safely.

This scientific progress, enhanced transparency and material innovation could be supported by lists of safe (classes of) substances and/or of widely recognised testing criteria (e.g. endocrine disruption, eco-toxicology, combination effects), which can build on existing initiatives and frameworks (e.g. REACH). For example, the ordinance by the Swiss Federal Department of Home Affairs sets out the only substances that can be used to manufacture packaging inks.[300] The Safer Chemical Ingredients List by the US EPA is a list of chemical ingredients, arranged by functional-use class, that the Safer Choice Program has evaluated and determined to be safer than traditional chemical ingredients.[301] CleanGredients® is another example of a database of chemical ingredients whose formulations have been pre-approved by the US EPA for use in Safer Choice-labelled products to help manufacturers find safer chemical alternatives.[302] More generally, the Cradle-to-Cradle certification process helps designers and manufacturers understand how chemical hazards combine with likely exposures regarding potential threats to human health and the environment. [303]

PART IV DECOUPLING PLASTICS FROM FOSSIL FEEDSTOCKS

9 DEMATERIALISATION: DOING MORE WITH LESS PLASTIC

Dematerialisation is the act of reducing or even eliminating the need for packaging, while maintaining utility. In the light of past impact and future trends, and in addition to the reuse options discussed in Chapter 5, three levers seem particularly promising for packaging dematerialisation: light-weighting; rethinking packaging design; and virtualisation. While at the moment an across-the-board substitution of plastics by other packaging materials would likely not be beneficial, material substitution could be a promising avenue for targeted applications and materials.

9.1 LIGHT-WEIGHTING IS AN IMPORTANT LEVER FOR DEMATERIALISATION, BUT WITH LIMITATIONS FROM A SYSTEMS PERSPECTIVE

The process of light-weighting packaging (i.e. reducing its mass) has achieved considerable material savings and will continue to be an important lever to improve efficiency of individual packaging products. However, from a systems perspective, it can create a lock-in effect and diminish overall system effectiveness.

9.1.1 Light-weighting innovation has already captured significant material savings, and is expected to continue doing so

Many companies have light-weighted their plastic packaging over the past 40 years, capturing significant material savings. Today, a one-litre washing-up liquid bottle uses 64% less material than in the 1970s, a 165g yoghurt pot 43% less, and a two-litre plastic fizzy drink bottle 31% less.[304] More recently, in their 2011/2012 Sustainability Report, Coca-Cola announced they had trimmed the weight of their 20-ounce PET bottles by more than 25%.[305]

Even after years of light-weighting, innovation is still having an impact. Unilever recently announced its MuCell Technology,[306] which reduces material density and hence the amount of plastic required by using gas injection to create gas bubbles in the middle layer of the material. The technology can be applied to bottles, sheets and films used for consumer packaging. Unilever believes that, if applied across all its categories, the technology could save up to 27,000 tonnes of plastic packaging every year.[307]

Such results attest to the remarkable innovation capabilities of the plastic packaging industry and should in itself be encouraged, but at the same time it should be taken into account that the light-weighting trend, particularly the evolution towards more complex formats, could have undesirable consequences from a systems perspective.

9.1.2 Balancing efficiency and effectiveness, the light-weighting paradox exposes a systems limitation

The light-weighting paradox is the tension between efficiency savings in production and usage, and effective after-use applications. If the after-use value of the packaging is too low, less will be recycled and more will leak outside collection systems. Reducing the material value of plastic packaging thus runs the risk of aggravating system leakage and creating a lock-in into a linear infrastructure by disincentivising circular after-use pathways.

This tension between efficiency and effectiveness is exposed by light-weighting single-material formats, and, as further efficiency gains in single-material formats have become harder to achieve, by the emerging trend of more complex multi-material packaging (see Box 4). These latter formats are an ultimate example of the paradox as they are often difficult to isolate in the waste stream and their complexity means recycling is not currently viable.[308] Innovation might offer a solution to these multi-material after-use challenges by replicating the utility and efficiency of multi-material composites using a single material and/or by designing reversible adhesives so the multi-material layers can be separated after use, or by developing innovative reprocessing techniques. While multi-material formats are a growing category, some manufacturers are looking for alternatives. For example, in 2014 Colgate-Palmolive committed to developing a recyclable toothpaste tube — current tubes are usually made from (non-recyclable) aluminium and plastic laminates.[309] Another example is the mono-material stand-up pouch recently developed by Dow Chemical, together with Printpack and Tyson Foods, which has improved recyclability versus the existing multi-material alternatives.[310]

9.2 RETHINKING THE PACKAGING CONCEPT ITSELF CAN BE AN IMPORTANT DEMATERIALISATION LEVER

By making material savings a higher priority in the design brief, stakeholders across the supply chain have found innovative solutions that reduce plastic packaging volumes and capture economic value, highlighting the potential for imaginative rethinking of the plastic packaging concept.

Several examples show how the rethinking of (plastic) packaging can create value. Mondelez (Cadburys) redesigned their boxed Easter Egg range so that there was no longer a need for the internal plastic thermoform. This simple change resulted in a 10% reduction in weight and achieved savings of over 1,000 tonnes of CO_2e through more efficient pallet and vehicle utilisation.[311] Unilever redesigned their bottles of Vaseline hand lotion, resulting in a reduction of pack weight of up to 15% since 2003, depending on pack size, compared to previous designs.[312] In The Disappearing Package, designer Aaron Mickelson demonstrates how rethinking the packaging concept could work for a number of packaged goods.[313] One example is the redesigned packaging for laundry detergent pods, which often are packed in a multi-material plastic pouch. Instead he proposes a solution in which the water-soluble pods would be stitched together forming a sheet, so the user can tear off a pod each time and use them one-by-one. With the last pod, the package itself is gone.

As consumer habits evolve there is increasing sensitivity to real or perceived over-packaging — some shoppers prefer to buy concentrated soaps instead of the diluted version requiring more plastic packaging.[314] Brands and retailers that take an innovative approach to their packaging designs could benefit from this trend.

9.3 NEW MATERIALS AND PRODUCTION TECHNOLOGIES COULD REPLACE TODAY'S PLASTICS IN SELECTED PACKAGING APPLICATIONS

Plastics are often not the only packaging material available. Traditional alternatives such as glass and metal typically offer better material loops, but are sometimes less desirable than plastics from a functional or life-cycle perspective — a case-by-case analysis is required. Next to the more traditional alternatives, several new substitutes continue to emerge, mostly based on innovations in material or production technologies. As they often have specific advantages and disadvantages, their ability to successfully replace plastic as a packaging material depends on the application. Hence, while an across-the-board substitution of plastics by other packaging materials would likely not be beneficial, material substitution could be a promising avenue for targeted applications and materials.

9.3.1 Innovative materials

Some of the more recent alternatives to plastic as packaging material use innovative materials, enhancing their after-use properties for selected applications, by being home compostable, water-soluble or even edible. In this way, these new materials can improve after-use pathways with often similar performance as plastics during use.

Ecovative's mushroom-based solution provides an alternative to polystyrene. Its Mushroom® packaging is literally grown to size using a crop waste feedstock. The process uses low levels of energy, produces no residue or waste (it is 'additive' in that sense), and the end product is shock-absorbing, fire resistant, and 100% home compostable.[315] Its deployment in some of DELL's bulky protective packaging is one of the success stories in the computer technology giant's quest for substitute packaging materials.

Polyvinyl alcohol (PVOH) is an alternative to plastic creating additional benefits thanks to being water-soluble, as explained in the following two examples. MonoSol has developed a range of PVOH-based films that are used in many applications. Dishwasher and laundry detergent tablets are common applications that reduce waste and leakage by individually wrapping portions of detergent in the water-soluble film. MonoSol also manufactures litter bags, medical laundry sacks and agrochemical packaging.[316] Splosh, the company that sells a range of cleaning products in a refillable system, distributes its active ingredients in PVOH sachets.[317] By dissolving in water PVOH adds viscosity and a mild cleaning action to the mixed solution.[318] By applying such a format, Splosh uses packaging to enhance the utility of their container reuse model.

Made from the shells of crustaceans, chitosan is an edible coating with excellent antimicrobial properties. Laboratory tests have shown that a chitosan-based coating, applied directly to vegetables, delays spoilage without affecting the quality of baby carrots.[319] It has also been demonstrated that chitosan-starch-blended films have higher flexibility and elongation properties than single polymer equivalents.[320]

Edible substitutes derived from organic feedstock are also being developed to meet a growing demand in the food packaging market. This market encompasses the sector of disposable

food wrappers, dishware, and cutlery at fast-food restaurants, hospitals, and other facilities, which is worth USD 20 billion in the United States alone.[321] WikiCell technology is a skin-like membrane that maintains freshness equal to current plastic packaging but is edible.[322] The membrane is made by binding molecules sourced from organic feedstock with carbohydrates and has already been adopted for a range of Stonyfield Organic frozen yoghurts sold through Whole Foods stores in Massachusetts, United States.[323] Furthermore, edible, biodegradable alternatives to single-use plastic containers are being developed from seaweed feedstock. In the United States, Loliware[324] makes FDA-approved cups using seaweed feedstock and organic sweeteners, flavours and colorants. London-based Ohoo![325] has developed a novel alternative to the water bottle, which The Global Design Forum called one of *'five ideas to shake the world'*.[326]

9.3.2 Innovative production technologies

Innovative production technologies could reduce the plastics volume required and simplify material content by building form and function into a single material. Nano-printing is such a technology that allows layering at the micron scale, meaning a material can be built from the bottom up in a LEGO®-like structure. Currently only available in laboratory conditions, the technology enables researchers to build various performance properties into one single material by structuring the 'bricks' in different patterns. Today, to achieve given properties like strength and flexibility manufacturers vary the amount of resin used or, for more complex properties like moisture and oxygen barriers, they combine multiple resin types in layered structures. Nano-printing could challenge these techniques and alter the way we think about plastics, and other materials, by using one material to get a variety of performance properties previously unavailable, while using less material.

Nature could serve as inspiration for this innovation. According to Alysia Garmulewicz of the Said Business School in Oxford: *'Cellulose is a simple polymer which exhibits complex behaviours when structured differently; nano-printing could enable manufacturers to mimic those performance outcomes by integrating the form and function of materials from the micro to macro scales.'*[327]

This may seem a futuristic concept but, under laboratory conditions, nano-printing is already achieving remarkable results. Material scientists at Harvard University can print at an accuracy of one micrometre (one-thousandth of a millimetre) and have already used the technology to print biological tissue interwoven with a complex network of blood vessels.[328] Given ever-improving degrees of accuracy, and provided adequate investment, there could be scope for researchers to recreate the performance of an organic compound like cellulose in synthetic materials like plastics.

9.4 VIRTUALISATION IS INCREASINGLY DISRUPTING TRADITIONAL DISTRIBUTION MODELS, REDUCING OR EVEN ELIMINATING THE NEED FOR PACKAGING

Virtualisation is the act of delivering utility virtually. It affects traditional distribution models, resulting in reduced, or even eliminated, need for plastic packaging. Examples in which utility is (partly) delivered virtually include the widespread use of digital music, movies and books, as well as emerging additive manufacturing technologies, commonly known as 3D printing, all of which change the requirements and necessity of packaging.

Progress in digital technologies, ranging from increased wireless internet access to falling costs of electronic devices, has boosted the adoption of digital versions of CDs, DVDs, books and magazines. Whether downloaded upfront or streamed online, the utility of these digital products is directly delivered to the customer in a virtual way, disrupting traditional distribution of hard copies and eliminating the need for packaging. The increase of online shopping also affects traditional distribution models by shipping the product directly from the wholesaler to the consumer. In this way, an intermediate player in the supply chain — the retailer — gets bypassed, simplifying distribution and reducing the need for packaging.

Additive manufacturing — an umbrella term for a family of technologies that use heat, light, binders, or pressure to build up materials layer by layer in accordance with a Computer Aided Design (CAD) file, and commonly known as 3D printing[329] — could change how and where goods are produced, and in turn change the requirements for and necessity of packaging.[330] Indeed, these technologies offer the potential for local, small batch production and thus could enable a system of local manufacturing referred to as *distributed manufacturing* that could change the role of packaging significantly. In this new paradigm the digital CAD file becomes the commodity. Once in possession of a CAD, a user could turn to any local manufacturer to have the design printed. Branding becomes virtualised and goods are produced closer to where demand arises. Today, the 3D Hubs platform connects users to a network of 25,000 3D printers with spare capacity, across 160 countries, giving over one billion people access to a 3D printer within 10 miles of their home. In 2014, all Fairphone cases sold in the company's

online shop were printed by machines connected to the 3D Hubs European network.[331] While still relatively small in scale, this is an example of a manufacturer adopting a disruptive new distribution model. Phone cases that usually come packaged in plastics clamshells or pouches were made redundant as the user collected the product from the point of production. Cost, speed, and accuracy place limits on widespread adoption but there is little doubt that additive manufacturing is a set of technologies with disruptive potential. The recent expiration of a number of patents is expected to trigger a wave of innovation,[332] and a future of distributed manufacturing is not unimaginable.[333] In this context, the demands on plastic packaging could be significantly different. For example, products travelling shorter distances through fewer (or no) distribution centres would require no packaging, or packaging with greatly reduced protective and storage properties.

10 RENEWABLY SOURCED PLASTICS: DECOUPLING PLASTICS PRODUCTION FROM FOSSIL FEEDSTOCKS

Even with tighter loops, diminished cycle losses and increasing dematerialisation, virgin feedstock is required to replace the plastics that are not looped back (e.g. due to composting or unintentional leakage). Sourcing such virgin feedstock from renewable sources — from greenhouse gases or biomass — helps decouple plastics production from finite fossil feedstocks and reduce the greenhouse gas footprint of plastic packaging.

10.1 RENEWABLY SOURCED PLASTICS ARE DERIVED FROM BIOMASS OR GREENHOUSE GASES

Renewably sourced plastics decouple the production of plastics from finite resources by sourcing the virgin feedstock either from captured greenhouse gases (GHG-based) or biomass (bio-based).

10.1.1 Virgin feedstock from biomass (bio-based feedstock)

As mentioned in Chapter 6, renewably sourced plastics, including bio-based plastics, are not necessarily compostable,[334] and compostable plastics are not necessarily bio-based. Bio-based plastics can be produced from different generations of feedstock:[335]

1st generation: Biomass from plants that are rich in carbohydrates and that can be used as food or animal feed (e.g. sugar cane, corn, and wheat).

2nd generation: Biomass from plants that are not suitable for food or animal feed production. They can be either non-food crops (e.g. cellulose) or waste materials from 1st-generation feedstock (e.g. waste vegetable oil, bagasse, or corn stover).

3rd generation: Biomass derived from algae, which has a higher growth yield than either 1st- and 2nd- generation feedstock, and therefore has been allocated its own category.

10.1.2 Virgin feedstock from captured greenhouse gases (GHG-based feedstock)

In this report, 'GHG-based plastics' refers to plastics for which the carbon used as a feedstock comes from the capture of greenhouse gases (GHG) such as carbon dioxide and methane. While not yet rigorously defined, GHG-based feedstock has already been coined '4th-generation feedstock' in a biofuel context.[336]

Methane and carbon dioxide can be captured from multiple sources. Methane, on the one hand, can be recovered — typically mixed with carbon dioxide — from landfills (as landfill gas), anaerobic digesters (as biogas), or coal mines (coal mine methane). Methane capture technology is relatively mature although biogas yields could still be improved in some cases.[337] For the production of PHA methane does not need to be cleaned. This makes capturing methane attractive as a feedstock for PLA compared to buying natural gas at market prices (natural gas still requires cleaning).[338]

Carbon dioxide, on the other hand, can be recovered as a by-product of industrial and chemical processes and is typically mixed with hydrogen and oxygen in different concentrations depending on the source.[339] Suitable sources for carbon dioxide capture include the cement industry, the production of iron, steel, and petrochemicals, and oil and gas processing.[340] However, given the chemical stability of carbon dioxide, breaking it into its components requires an efficient catalytic system and a significant amount of energy — both of which come at a cost.[341]

In contrast to carbon dioxide, methane can already be captured and utilised, for example, for the production of energy and electricity (as is often the case in anaerobic digestion plants). Hence, in the scenario of high utilisation of methane for energy and electricity production, capturing carbon dioxide for plastics production comes with the benefit that a higher share of overall GHG emissions could be captured and utilised.[342]

10.1.3 Drop-ins and new materials

Based on their physical and chemical properties, renewably sourced plastics can be divided into two categories: drop-ins and new materials. Currently, bio-based plastics can either be drop-ins (e.g. bio-PE, bio-PET) or new materials (e.g. PLA, starch-based materials) whereas GHG-based plastics are mainly new materials such as PHA.

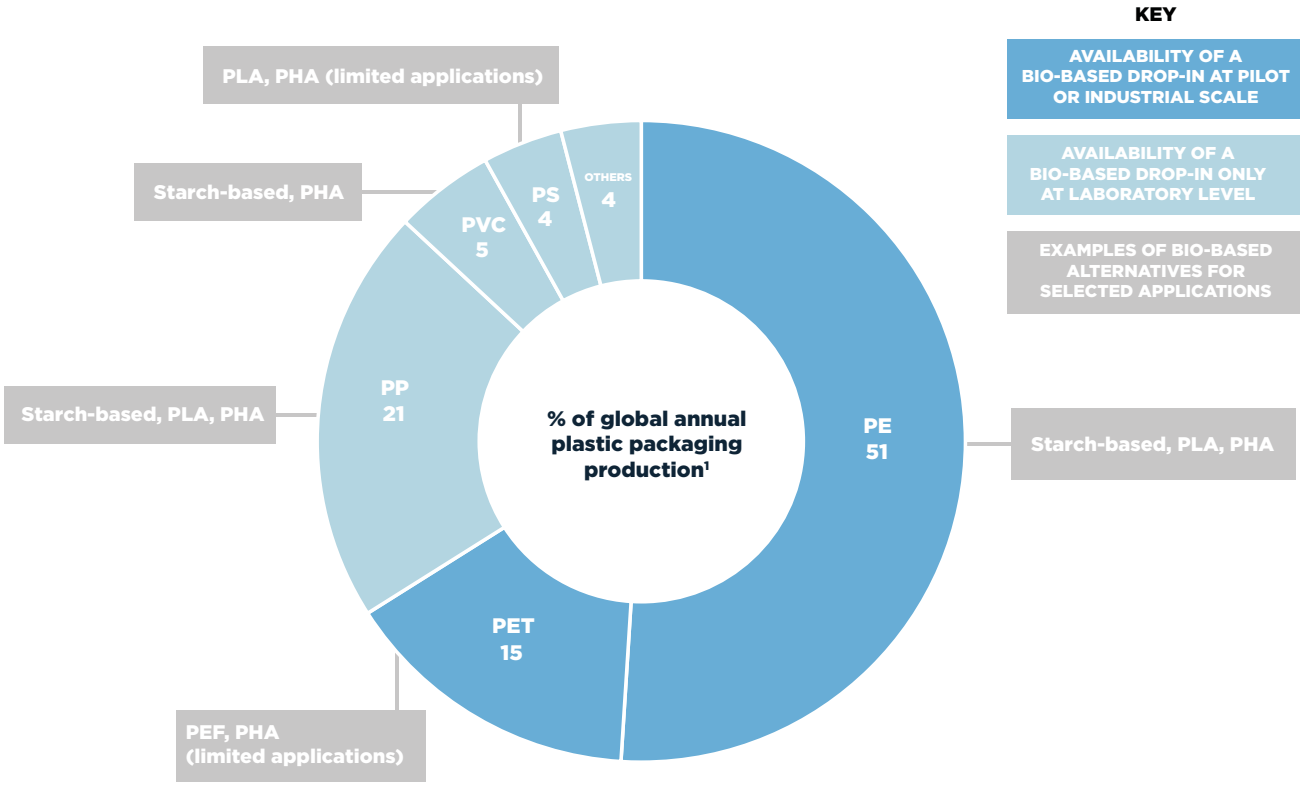
Drop-ins are identical, renewably sourced counterparts to fossil-based plastics currently in use (e.g. bio-based PE for PE, bio-based PET for PET). They have the exact same chemical and physical properties, which means that they can

be used seamlessly in the existing value chains before and after use and deliver the same level of performance: packaging companies do not need to change their equipment or processes to handle the drop-ins; distributors and retailers get the same performance; and drop-ins can be collected and recycled alongside their fossil-based counterparts, in the same systems.

As shown in Figure 19, 60% of the plastics used for packaging purposes today could technically be replaced by drop-ins.

New materials have different chemical and physical properties to current fossil-based plastics (e.g. PLA, PHA). These new materials can be used in a wide range of packaging applications. Standard PLA, for example, is used in applications such as single-use food service packaging, yoghurt pots, or plastic bags.[343] Some barriers[344] (e.g. to CO_2 and oxygen), mechanical, and processing properties do not necessarily match those of fossil-based plastics (e.g. PP, PET), but can be enhanced through the use of additives.[345] New materials such as PLA and PHA can theoretically be mechanically recycled though they lose some physical properties after several cycles. Laboratory research is being conducted to develop new bio-based polymers that can be recycled without their physical properties degrading.[346]

FIGURE 19: OVERVIEW OF BIO-BASED DROP-INS AND NEW MATERIAL ALTERNATIVES FOR MAJOR RESIN TYPES



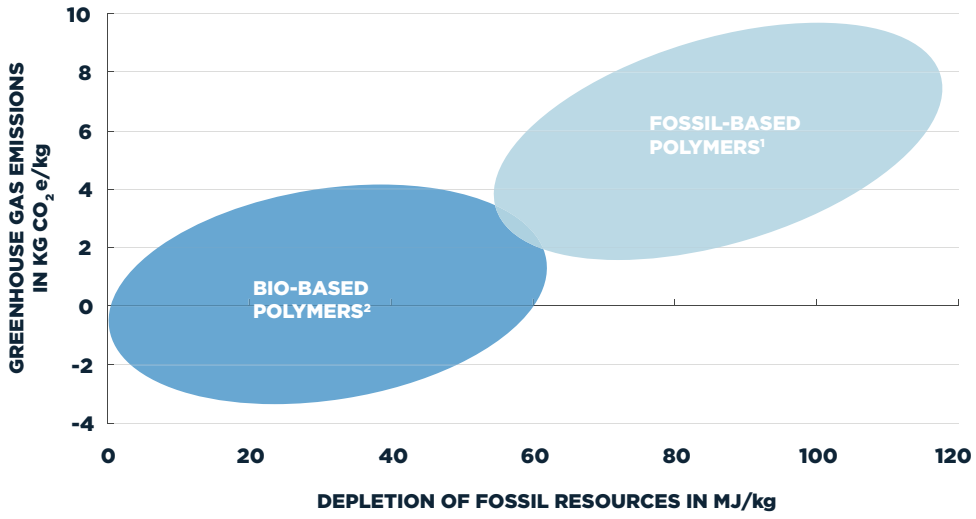
1 Based on distribution in Germany and extrapolated to global volumes

Source: PlasticsEurope, *An analysis of European plastics production, demand and waste data* (2015); Industrieverband Kunststoffverpackungen, *2014/15 annual report* (2015).

10.2 RENEWABLY SOURCED PLASTICS CAN HELP DECOUPLE PLASTICS PRODUCTION FROM FINITE FEEDSTOCKS AND REDUCE GREENHOUSE GAS EMISSIONS

Besides decoupling virgin feedstock from finite resources, renewably sourced plastics can, under certain conditions, decrease carbon dioxide emissions and potentially act as a carbon sink throughout their life cycle. For plastics sourced directly from captured greenhouse gases such as methane and carbon dioxide, this link is clear.[347] For bio-based plastics, this happens indirectly: plants capture carbon dioxide from the atmosphere as they grow and this carbon is then harnessed in the polymer.[348] The carbon footprint of PE, for example, has been found to be -2.2 CO_2e per kilogram of bio-based PE produced compared to 1.8 CO_2e per kilogram of fossil-based PE produced.[349] A comparison of fossil-based and bio-based polymers in terms of their greenhouse gas emissions and depletion of fossil resources is shown in Figure 20 (such an analysis has yet to be conducted for GHG-based feedstock).

FIGURE 20: ENVIRONMENTAL IMPACTS OF DIFFERENT POLYMERS IN TWO IMPACT CATEGORIES



1 PP = Polypropylene, HDPE = High density polyethylene, LDPE = Low density polyethylene, PET = Polyethylene terephthalate, PS Polystyrene, PC = Polycarbonate

2 Bio-based PLA (Polylactic acid), bio-based PHA (Polyhydroxyalkanoate), bio-based PE (Polyethylene)

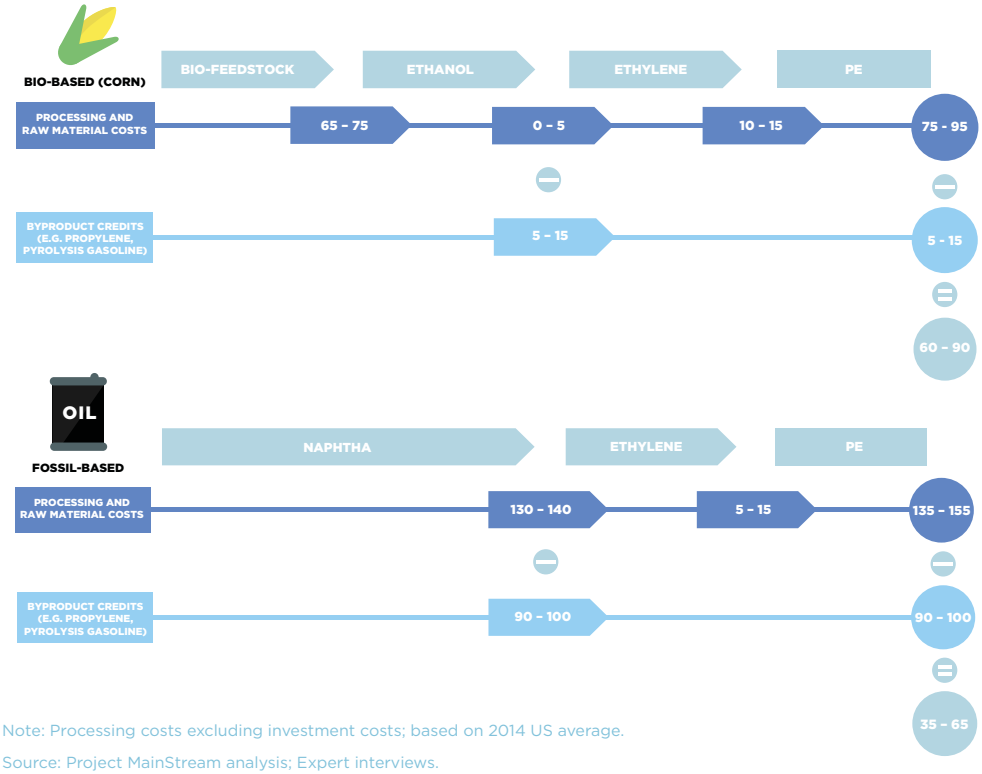
Source: nova-institut.

10.3 BIO-BASED PLASTICS ARE CURRENTLY THE LARGEST RENEWABLY SOURCED SEGMENT, BUT OFTEN HAVE CHALLENGING ECONOMICS AND CAN HAVE UNDESIRED SIDE EFFECTS

In 2014, 1.7 million tonnes of bio-based plastics were put on the market (approximately 0.6% of total plastics).[350] Some forecasts expect bio-based plastics production to increase to 7.9 million tonnes in 2019,[351] mainly driven by the production of drop-ins.[352] The largest drop-ins in terms of volume are bio-PET and bio-PE (35.4% and 11.8% of total bio-based plastics production[353]). The growth of these drop-ins is mainly driven by the demand of large companies, such as Coca-Cola — whose bio-based PET bottles currently contain 30% bio-PET, but which, it has been announced, will consist of 100% bio-PET in the future[354] — and Braskem, which uses bio-PE sourced from sugarcane in Brazil.[355] The biggest segments in the new materials category are PLA and blends of biodegradable polyesters that are produced on a large scale and expected to grow from 0.2 million tonnes in 2014 to 0.4 million tonnes in 2019.[356]

However, the production of bio-based plastics is currently often not cost-competitive with fossil-based plastics. Bio-based plastics can cost significantly more than their fossil-based counterparts,[357] depending on the production scale, level of optimisation, and the material produced. This price difference is driven by the cost of raw materials and the processing steps required to create the feedstock (Figure 21). For example, bio-PE and bio-PP sell at ~30% premium compared to fossil-based PE[358] and PP,[359] and PLA is about twice as expensive as PE though it can be price competitive with polystyrene for some applications because it requires thinner walls and hence can be used in smaller amounts.[360]

FIGURE 21: BIO- AND FOSSIL-BASED ROUTES FOR PRODUCTION OF POLYETHYLENE AND INDICATIVE COSTS



Note: Processing costs excluding investment costs; based on 2014 US average.

Source: Project MainStream analysis; Expert interviews.

Fossil-based plastics supply chains have benefited from several decades of operations at scale, allowing for multiple cost optimisation exercises. In contrast, bio-based feedstock supply chains are not yet scaled and hence many cost optimisation levers are not yet available.

If price parity with fossil-based plastics is difficult to achieve, it is possible that businesses and individuals might be prepared to pay a moderate price premium for bio-based (as well as GHG-based) plastics. Their reasons for paying more for renewably sourced plastic could include the greater flexibility of some materials in the after-use phase (e.g. PLA is in theory both recyclable and compostable); new performance characteristics; and because end users might be prepared to pay more for renewably sourced materials.

The impact of bio-based plastics, and the bio-economy in general, on issues such as land use, competition with food and impacts on agricultural processes as well as biodiversity have received widespread attention.[361] Fully assessing the impact of bio-based feedstock on these issues is a complex endeavour. However, negative externalities could be reduced by applying regenerative principles in the agricultural processes, for example.[362]

10.4 GHG-BASED PLASTICS ARE A PROMISING SEGMENT, BUT VIABILITY AT SCALE STILL NEEDS TO BE PROVEN

Using captured GHG as a feedstock decouples plastic production from finite fossil-based resources, utilises feedstock that is widely available at low cost, and leverages plastics as a GHG sink — potentially creating materials with a negative carbon footprint.[363] GHG-based plastics also come with the inherent benefit that feedstock production does not have undesired side-effects such as impact on land use or biodiversity. As a result, the production of plastics from captured GHG has been an important research topic for companies and academics.

Building on recent technological progress, some companies are now at a stage of scaling up their production. Newlight, for example, has recently signed a binding off-take agreement with Vinmar for 1 billion pounds over 20 years (approximately 450 thousand tonnes).[364] In addition, there is a *'possible expansion of the contract for delivery to Vinmar of up to 19 billion pounds [8.6 million tonnes] over the same two decades'* and production capacity is planned to be scaled up with 50-million, 300-million and 600-million-pound facilities (approximately 23 thousand tonnes, 136 thousand tonnes and 272 thousand tonnes respectively).

Novomer announced a *'large-scale manufacturing run of polypropylene carbonate (PPC) polyol'*.[365] Bayer MaterialScience plans to open a new plant in 2016, which will have a capacity of several thousand tonnes.[366]

Currently, production of PHA from methane capture (e.g. Newlight and Mango Materials) and polyurethane from carbon dioxide capture (e.g. Bayer MaterialScience) are most common. PHA can be used in a wide range of applications (e.g. cutlery, cups, films, bottles, surgical tools) and could replace fossil-based plastics such as PE or PET. Polyurethane is used, for example, to produce foams.[367] However, there are also other materials. Novomer, for example, produces polyols (40% carbon dioxide), which can be used subsequently in the polyurethane production process.[368]

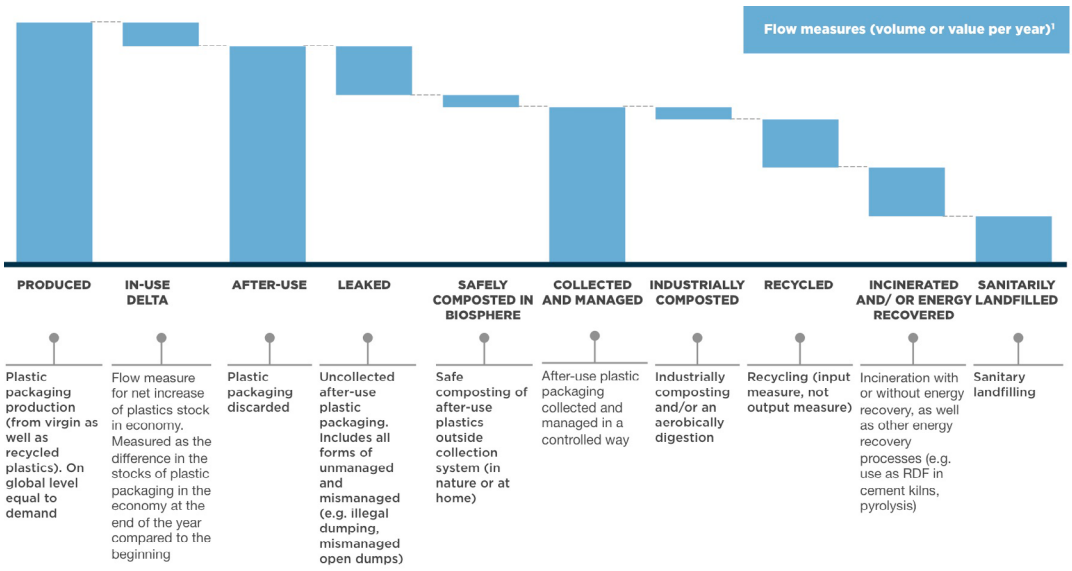
Some companies claim that GHG-based materials are cost-competitive with current fossil-based plastics (e.g. PE, PP, PVC) at pilot level. However, production costs might increase if production at scale requires access to additional and potentially less profitable sources of GHG than those currently available for smaller production batches. Hence cost-competitiveness and viability at scale still need to be proven.[369]

APPENDICES

APPENDIX A. GLOBAL MATERIAL FLOW ANALYSIS: DEFINITIONS AND SOURCES

This analysis of the global flows of plastic packaging materials is based on an aggregation of fragmented data sets, often with varying definitions and scope. The analysis not only reveals a significant opportunity to increase circularity and capture material value, but also highlights the need for better alignment of reporting standards and consolidation on a global level. Specific efforts could be dedicated to improving the data from developing markets with informal waste sectors.

FIGURE A1: DEFINITIONS FOR OVERVIEW OF GLOBAL PLASTIC PACKAGING MATERIAL FLOWS



1 Including domestically collected waste only (no imported waste), irrespective of where (locally or abroad) it is processed (landfilled, incinerated or recycled)

2 Landfills in low-income countries are considered dump sites according to the definitions used by J. R. Jambeck et al. Given small volumes this assumption does not significantly affect numbers

Source: PlasticsEurope; Transparency market research.

FIGURE A2: DETAILED CALCULATIONS AND ASSUMPTIONS BEHIND GLOBAL PLASTIC PACKAGING MATERIAL FLOWS (1/2)

GLOBAL PLASTIC PACKAGING, 2013

	METRIC	VALUE	METRIC	SOURCE/COMMENTS
PRODUCED	Plastic packaging production/ demand	78.4	Mn tonnes	Demand based on Transparency Market Research, Plastic Packaging market analysis.
IN-USE DELTA	Plastic packaging market growth	4.8	% p.a.	2014-2020 expected growth, Transparency Market Research, Plastic Packaging market analysis
	× Plastic packaging demand	78.4	Mn tonnes	Transparency Market Research, Plastic Packaging market analysis
	× Average plastic packaging life time	0.25	Years	Assumption
	= Delta of packaging in-use	0.9	Mn tonnes	Calculated
AFTER-USE	After-use	77.5	Mn tonnes	Calculated as demand minus growth in in-use plastic packaging
LEAKED	Plastic packaging after use	77.5	Mn tonnes	Calculated as demand minus growth in in-use plastic packaging
	× Share of plastics mismanaged	32	%	J. R. Jambeck et al. (2015)[1] for coastal countries (93% of population), assumed to be valid globally and for plastic packaging
	= Leakage	25	Mn tonnes	Calculated
COLLECTED AND MANAGED	Plastic packaging collected	53	Mn tonnes	Calculated as after-use minus leakage and mismanagement
RECYCLED	Recycling rate	20.8	%	Weighted average based on EU27+2 data, US data and World Bank estimates for rest of world
	× Plastic packaging collected	53	Mn tonnes	Calculated as after-use minus leakage and mismanagement
	= Plastic packaging recycled	11	Mn tonnes	Calculated
INCINERATED AND/OR ENERGY RECOVERED	Incineration and/or energy recovery rate	20.4	%	Weighted average based on EU27+2 data, US data and World Bank estimates for rest of world
	× Plastic packaging collected	53	Mn tonnes	Calculated as after-use minus leakage and mismanagement
	= Plastic packaging incinerated and/or energy recovered	11	Mn tonnes	Calculated
SANITARILY LANDFILLED	Landfill rate	58.8	%	Weighted average based on EU27+2 data, US data and World Bank estimates for rest of world
	× Plastic packaging collected	53	Mn tonnes	Calculated as after-use minus leakage and mismanagement
	= Plastic packaging landfilled	31	Mn tonnes	Calculated

1 Jambeck et al., *Plastic waste inputs from land into the oceans* (2015)

FIGURE A2: DETAILED CALCULATIONS AND ASSUMPTIONS BEHIND GLOBAL PLASTIC PACKAGING MATERIAL FLOWS (2/2)

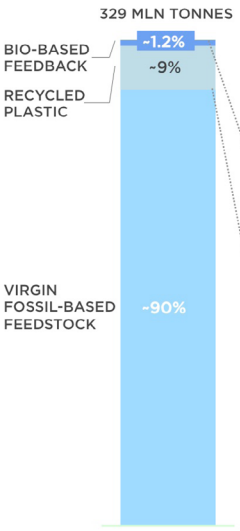
GLOBAL PLASTIC PACKAGING, 2013, DEEP DIVE GLOBAL RECYCLING, INCINERATION/ENERGY RECOVERY AND LANDFILL RATES

	METRIC	VALUE	METRIC	SOURCE/COMMENTS
EU27+2 (2012)	Plastic packaging recycled	5.4	Mn tonnes	http://www.epro-plasticsrecycling.org/pages/75/epro_statistics
	Plastic packaging to incineration and/or energy recovery	5.4	Mn tonnes	Based on 34.5% by PlasticsEurope, *Plastics – the Facts 2013*, page 29
	Plastic packaging landfilled sanitarily	4.8	Mn tonnes	Based on 30.8% by PlasticsEurope, *Plastics – the Facts 2013*, page 29
US (2012)	Plastic packaging recycled	1.9	Mn tonnes	US EPA, Plastic containers and packaging data
	Plastic packaging to incineration and/or energy recovery	2.1	Mn tonnes	US EPA, Plastic containers and packaging data
	Plastic packaging landfilled sanitarily	8.7	Mn tonnes	US EPA, Plastic containers and packaging data
REST OF WORLD (WORLD BANK DATA INCL. DATA OF DIFFERENT YEARS FOR DIFFERENT COUNTRIES)	Global plastic packaging collected and sanitarily managed	53	Mn tonnes	See figure above
	− Plastic packaging collected and sanitarily managed in EU27+2 and US	28	Mn tonnes	See above
	= RoW plastic packaging collected and sanitarily managed	24	Mn tonnes	Calculated (does not sum up due to rounding)
	× RoW plastic packaging recycling rate	15	%	Based on World Bank data, *What a waste: A Global Review of Solid Waste Management* (2012) for MSW and converted to plastic packaging based on (EU +US) ratio between rates for MSW and plastic packaging
	RoW plastic packaging incineration and/or energy recovery rate	13	%	
	RoW plastic packaging sanitary land fill rate	72	%	
	= RoW plastic packaging recycled	4	Mn tonnes	Calculated
	RoW plastic packaging to incineration and/or energy recovery	3	Mn tonnes	Calculated
	RoW plastic packaging sanitarily landfilled	17	Mn tonnes	Calculated

FIGURE A3: SOURCES FOR GLOBAL PLASTICS PRODUCTION CALCULATION

GLOBAL PLASTIC PRODUCTION VOLUME BY SOURCE MATERIAL

2013, %



METRIC	YEAR	AMOUNT	UNIT	SOURCE/COMMENTS
▪ Bio-based polymers production capacity[1]	2013	5.13	Mn tonnes of bio-based content	▪ nova-Institute, '*Bio-based Building Blocks and Polymers in the World*' (2013)
▪ Capacity utilisation rate	2013	80	%	▪ Assumption by nova-Institute
▪ Recycling input	2013	42	Mn tonnes	▪ Pöyry, 2013
▪ Average recycling yield	2012	72	%	▪ Deloitte report[2] (Data provided by European recyclers through PRE)
▪ Global virgin plastic production	2013	299	Mn tonnes	▪ PlasticsEurope ▪ Including thermoplastics, polyurethanes, thermosets, adhesives, coatings, sealants and PP bers ▪ Excluding bio-based plastics mentioned above

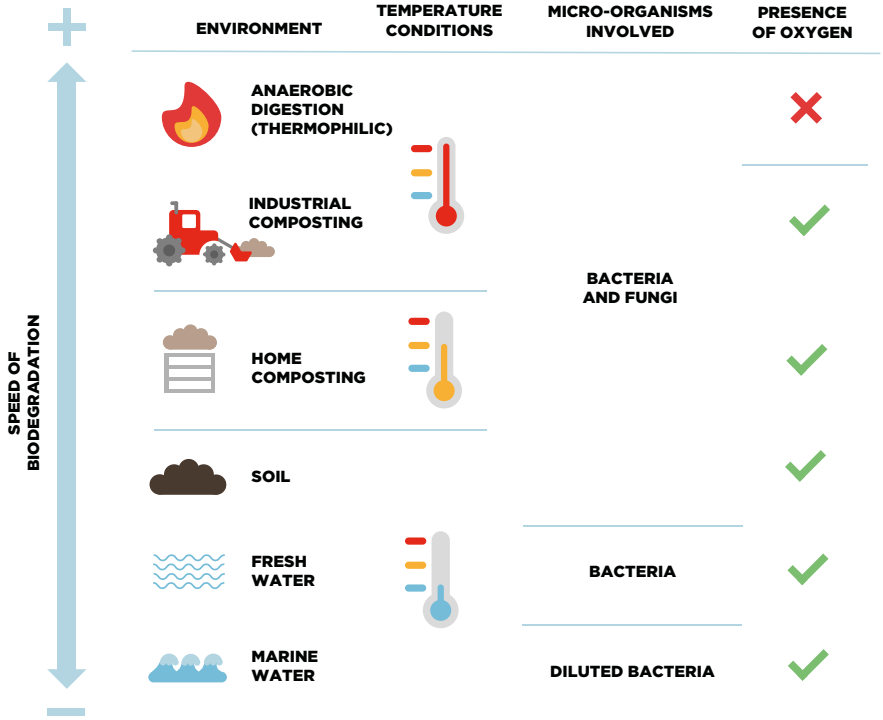
1 1.6 mn tonnes reported by European Bioplastics (PA, PBAT, PBS, PE, PET, PHA, PLA, PTT and starch in plastic compounds) plus biobased thermosets (epoxies (1.2 mn tonnes), polyurethanes (1.2 mn tonnes) and ethylene propylene diene monomer rubber (0.04 mn tonnes)) and cellulose acetate (0.9 mn tonnes)

2 Deloitte, *Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment* (2015)

APPENDIX B. BIODEGRADATION

Biodegradation is a bio-chemical process in which materials, with the help of micro-organisms, break down into natural elements (e.g. water, carbon dioxide, new biomass). The availability of oxygen determines which molecules the organic carbon is converted to (partly into carbon dioxide in the presence of oxygen, partly into methane without oxygen).[370] There are schemes and standards to certify that a material biodegrades in a specific environment within a specified timescale. However, this does not mean that such a material biodegrades in any environment within a short timescale. Industrially compostable materials, for example, are biodegradable (i.e. they break down into natural elements with the help of micro-organisms) within the conditions and timescale specified in industrial composting standards. However, they do not biodegrade in home composting [lower temperature] conditions within the same timescale. Hence, the term 'biodegradable' is very broad and can easily be misinterpreted. As pointed out by European Bioplastics, *'"biodegradable" by itself is not more informative than the adjective "tasty" used to advertise food products'*.[371]

FIGURE B1: RELATION BETWEEN ENVIRONMENT AND SPEED OF BIODEGRADATION



Source: Building on B. De Wilde et al., *Report on current relevant biodegradation and ecotoxicity standards* (2013).

Oxo-degradable (or oxo-fragmentable) plastics are conventional materials that are combined with additives that trigger fragmentation of the plastics triggered by heat or UV irradiation.[372] As explained in Box B1, oxo-fragmentable plastics are not proven to biodegrade[373] and the fragments could increase the level of microplastics in the oceans and hence their environmental benefits are questionable. Oxo-fragmentable plastics are not recommended, until innovation unlocks safe and complete biodegradability of such materials that is backed up by a solid fact base and consensus of the scientific community.

Box B1: Additive-mediated fragmentation (e.g. oxo-fragmentation)

Additive-mediated fragmentation entails that a conventional plastic is combined with special additives, which trigger the degradation of the product.[374] Additive-mediated conventional plastics can be either oxo-fragmentable or enzyme-mediated plastics; as pointed out in a recent report by European Bioplastics, these plastics do not biodegrade as defined by the norm EN 13432 for industrial composting (see Box 3 in Chapter 3 for a more detailed discussion).[375]

Oxo-fragmentable plastics are conventional plastics (e.g. PE, PP, PS, PET, PVC) that are combined with additives that trigger fragmentation of the plastics triggered by heat or UV irradiation.[376] OWS, a company specialised in anaerobic digestion, states in a report that *'the term oxo-degradable (oxo-fragmentable) plastics is being used for commercial reasons but is not yet standardised [...] and not yet unanimously*

utilised or accepted by the industry'.[377]

In the current state of the technology, oxo-fragmentable plastics do not seem to be a viable option. The benefits provided by oxo-degradable plastics are being questioned. An extensive literature study by OWS in 2013 could only find *'two scientific articles indicating a considerable percentage of biodegradation of oxo-degradable material. All other articles reported no or only a (very) low level of biodegradation'*. Therefore they concluded that *'the rate and level of biodegradation of oxo-degradable plastics are at least questionable and irreproducible'* and that *'oxo-degradable plastics do not meet the requirements of industrial and/or home composting'*.[378] Given the questionable benefits, and the potential damage these materials can cause if they enter the recycling stream, the EU Commission is debating a potential ban.[379] Two UK supermarkets, Tesco and the Co-operative Food, have already stopped using oxo-degradable bags.[380]

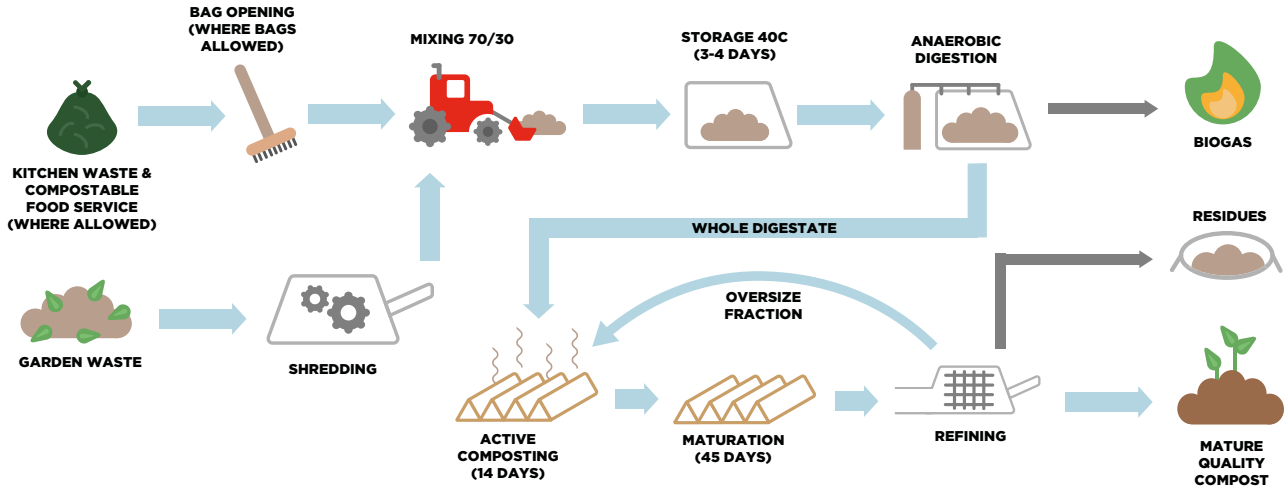
APPENDIX C. ANAEROBIC DIGESTION

In the anaerobic digestion process organic matter is broken down by a microbial population of bacteria in the absence of oxygen.[381] The carbon of the material is partly converted to biogas, which is a mixture of carbon dioxide (25–50%) and methane (50–75%)[382] and, depending on the composition of the feed, several trace compounds.[383]

There are several types of anaerobic digestion plants. They are mainly distinguished by their temperature (mesophilic between 35 and 40 °C and thermophilic between 55 and 60 °C), their moisture content (wet below 15% of solid matter by weight, dry above 15%) and their regime of digesters which can be continuous or in batch.

Wet reactors are necessarily fed by a continuous process. Wet mesophilic and dry (mesophilic and thermophilic) systems are the dominant systems for the digestion of solid materials including food waste. As WRAP explains, 'the system chosen will largely depend on the feedstock to be processed. For example, "high solids", such as garden and food waste mixture, tend to be processed at a thermophilic temperature using the batch system, while "low solids", such as animal slurry mixed with industrial and municipal food wastes, are more likely to be processed at a lower temperature using a continuous flow system.'[384]

FIGURE C1: PROCESS OF A DRY MESOPHILIC ANAEROBIC DIGESTER



Source: Process scheme of the Smartferm AD plan in California by Christian Garaffa in: Open-Bio, Review on standards for biogasification.

Currently, there is no standard to define the biodegradability of materials in an AD environment.[385] The biodegradation behaviour of products under aerobic composting conditions is not identical to that under anaerobic conditions (e.g. different fungi activity, temperatures, pretreatments) and hence a product that is degraded under industrial composting conditions might pass through an AD plant unaltered. For example, a thick PLA packaging will go through a mesophilic AD plant without significant biodegradation or disintegration and would be in the digestate if spread onto the land. Therefore, anaerobic digestion is often preceded by a pretreatment step and followed by an industrial composting step.

GLOSSARY

Anaerobic digestion (AD)	Anaerobic digestion is a process in which organic matter is degraded by a microbial population of bacteria in the absence of oxygen.
After-use pathway	A defined route that a material travels and the process steps it undergoes to be redeployed or disposed of, following its initial use cycle. Materials not being defined and controlled after-use pathways are referred to as 'leakage'.
B2C	Business to consumer.
B2B	Business to business.
Bio-based	A material is bio-based if it is wholly or partly derived from biomass.
Bio-benign	A material is bio-benign if it is harmless to natural systems in case it unintentionally escapes collection and recovery systems.
Biodegradable	A material is biodegradable if it can, with the help of micro-organisms, break down into natural elements (e.g. water, carbon dioxide, biomass).
Chemical recycling	A process to break down polymers into individual monomers or other chemical feedstock that are then be used as building blocks to produce polymers again.
Compostable	Compostable materials can be either industrial or home compostable, see below.
Cracking	In this report cracking refers to chemical processes that break down polymers into a wide range of hydrocarbon products. This can include thermal processes (e.g. pyrolysis, gasification) or catalytic cracking processes.
Decomposition or degradation	The process of molecular unbinding of a compound due to physical, chemical or biological actions (e.g. UV exposure, temperature, microbial activity) that may lead to the loss of the initial properties of the compound.
Dematerialisation	The act of reducing or even even eliminating the need for materials in a product, while maintaining its utility.
Depolymerisation	In this report depolymerisation refers to chemolytical processes (e.g. hydrolysis, methanolysis, glycolysis, aminolysis, etc) that break down polymers and produce mainly the monomers from which they have been produced or other oligomers (short chains of monomers). These can then be used as building blocks for the production of new polymers. These processes only apply to condensation polymers like polyesters (e.g. PET, PLA) and polyamides (e.g. nylon).
Drop-in	Renewably sourced counterparts of fossil-based plastics currently in use (e.g. bio-PE for PE, bio-PET for PET), with the same chemical and physical properties.
EPS	Expanded polystyrene. A rigid tough product, made from polystyrene beads that have been expanded and packed to form a closed cellular foam structure.
Feedstock	Any bulk raw material that is the principal input for an industrial production process.
Fragmentation	The process by which plastics break into pieces over time. A plastic can fragment into microscopic pieces while not being biodegradable.

GHG-based	A material is GHG-based if it is wholly or partly derived from greenhouse gases such as carbon dioxide or methane.
Greenhouse gas (GHG)	Any gaseous compound that is capable of absorbing infrared radiation. By trapping and holding heat in the atmosphere, greenhouse gases are responsible for the greenhouse effect, which ultimately leads to climate change.
Global plastics protocol	A core set of standards and guidelines that establish design, labelling, marking, infrastructure and secondary market standards, allowing for regional differences and innovation.
HDPE	High-density polyethylene, a type of polymer.
Home compostable	Compostable in an uncontrolled environment (under naturally occurring conditions).
Industrially compostable	Compostable in a controlled environment.
LDPE	Low-density polyethylene, a type of polymer.
Leakage	Materials that do not follow an intended pathway and 'escape' or are otherwise lost to the system. Litter is an example of system leakage.
Light-weighting	Design and manufacturing processes that reduce packaging mass.
Linear	Used in the context of the linear economy; linear refers to any process that follows the straight line of take, make and dispose. Once a material has been used for its intended purpose it is discarded and lost to the system.
Mechanical recycling	Operations that recover after-use plastics via mechanical processes (grinding, washing, separating, drying, re-granulating, compounding), without significantly changing the chemical structure of the material.
Natural capital	Natural capital refers to the world's stocks of natural assets, which include geology, soil, air, water, and all living things.
Physical Internet	A concept (or vision) for an open global logistics system founded on physical, digital, and operational interconnectivity.
PET	Polyethylene terephthalate, a type of polymer.
Plastics	Polymers that include thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants and PP fibres.
Plastic lumber (PL)	Construction material that can be used as an alternative to wood. Can be made from 100% recycled plastic.
Plastic packaging	A sub-set of plastic usage, referring to all packaging made of plastic material. This report includes rigid (e.g. bottles, jars, canisters, cups, buckets, containers, trays, clamshells) and flexible (e.g. bags, films, foils, pallet shrouds, pouches, blister packs, envelopes) plastic packaging, for both consumer and industrial purposes.
Polymer	Natural or synthetic macro-molecules composed of many repeated sub-units bonded together; plastics are typically organic polymers.

PP	Polypropylene, a type of polymer.
PS	Polystyrene, a type of polymer.
PVC	Polyvinyl chloride, a type of polymer.
Pyrolysis	A process of thermochemical decomposition of organic material at elevated temperatures and in the absence of oxygen.
Recyclate	Waste material that is to be sold and used for recycling in manufacturing; secondary material.
Renewably sourced	Derived from renewable sources, either biomass or captured greenhouse gases.
Resin	A natural or synthetic solid or viscous organic polymer used as the basis of plastics, adhesives, varnishes, or other products.
Substances of concern	Chemical elements and their compounds that may have serious and often irreversible effects on human health or the environment.

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ENDNOTES

1 This report uses the following definition of 'plastics': 'Polymers that include thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants and PP-fibres.' This definition is based on PlasticsEurope, *Plastics – The Facts 2014/2015* (2015).

2 A. T. Kearney, *Plastics: The Future for Automakers and Chemical Companies* (2012).

3 A. Anrady and M. Neal, *Applications and societal benefits of plastics* (Philosophical Transactions of the Royal Society B, 2009).

4 Ibid.

5 PlasticsEurope, taken from a chart in United Nations Environment Programme, *UNEP Year Book 2014: Emerging issues in our Global Environment* (2014), Chapter 8: Plastic Debris in the Ocean.

6 Share of 26% is based on 78 million tonnes of plastic packaging and 299 million tonnes of plastics production in 2013 (Transparency Market Research, *Plastic Packaging Market: Global Industry Analysis, Size, Share, Growth, Trends and Forecast, 2014–2020* (2015); PlasticsEurope, *Plastics – the Facts* (2015)). Other sources claim a higher share of packaging as a percentage of the plastics market, but data on a global level on plastics and plastic packaging in one publicly available source has not been found. Acknowledging the need for further efforts to harmonise data sets and reporting on a global level, this report builds on the two public sources outlined above. As the share of 26% might be on the lower side, figures such as the size of the market and the material value to be captured could even be larger than currently presented.

7 Euromonitor, *Off-trade and retail plastics packaging volume* (2015).

8 This report uses the following definition of 'plastic packaging': 'Including rigid (e.g. bottles, jars, canisters, cups, buckets, containers, trays, clamshells) and flexible (e.g. bags, films, foils, pallet shrouds, pouches, blister packs, envelopes) plastic packaging for 'consumer' and industrial purposes.' This is based on Transparency Market Research, *Plastic Packaging Market: Global Industry Analysis, Size, Share, Growth, Trends and Forecast, 2014–2020* (2015).

9 Euromonitor, *Off-trade and retail plastics packaging volume* (2015).

10 Transparency Market Research, *Plastic Packaging Market: Global Industry Analysis* (2015).

11 Based on 4.8% growth rate 2013–2020 (Technavio forecast of April 2015 for market growth over the period 2014–2019); 4.5% for 2021–2030 (ICIS), and 3.5% for 2031–2050, using a conservative assumption of growth beyond 2030 following the long-term trend in global GDP growth of 3.5% annually (International Energy Agency, *World Energy Outlook 2015* (2015)).

12 International Council of Forest and Paper Associations, *Statement on Paper Recycling* (2014).

13 United Nations Environment Programme, *Recycling Rates of Metals: A Status Report* (2011).

14 Polyethylene terephthalate. This resin is commonly used in beverage bottles and many injection-moulded consumer product containers. It is clear and tough, and has good gas and moisture barrier properties (source: American Chemistry Council).

15 Project MainStream analysis.

16 For this analysis, natural gas liquids are included in the oil category. This is in line with the definitions used by the International Energy Agency. Project MainStream analysis drawing on sources including BP, *Energy Outlook 2035* (February 2015); IEA, *World Energy Outlook* (2014); J. Hopewell et al., *Plastics recycling: Challenges and opportunities* (Philosophical Transactions of the Royal Society B, 2009); and PlasticsEurope, *Plastics – the Facts* (2015).

17 IEA, *World Energy Outlook* (2014).

18 The midpoint of the 4–8% range referred to in Section 1.2.2 is taken as the plastics' industry share of global oil production and growth rates of consumption in line with projected industry growth of 3.8% annually 2015–2030 (ICIS) and 3.5% annually 2030–2050 (International Energy Agency *World Energy Outlook 2015* (2015)). (BP notes that increases in efficiency are limited BP, *Energy Outlook 2035*, (February 2015)).

19 In its central New Policies scenario, the International Energy Agency in its *World Energy Outlook 2015* projects that oil demand will increase by 0.5% annually 2014–2040.

20 United Nations Environment Programme, *Valuing Plastic: The Business Case for Measuring, Managing and Disclosing Plastic Use in the Consumer Goods Industry* (2014). The research was conducted by natural capital analysts Trucost on behalf of the Plastics Disclosure Project (PDP). Both figures (USD 75 billion and USD 40 billion) only consider the natural capital costs of consumer goods. By also considering externalities of other segments such as medical, tourism/hospitality, transport etc. the natural capital costs would be even higher. 'Natural Capital can be defined as the world's stocks of natural assets which include geology, soil, air, water and all living things' (Natural Capital Forum, http://naturalcapitalforum.com/about/). Profit pool estimated based on plastic packaging market revenues of USD 260bn and an average EBITDA margin range of 10–15%, the global plastic packaging profit pool is estimated to be USD 26–39bn (sources: Transparency Market Research, *Plastic Packaging Market — Global Industry Analysis, Size, Share, Growth, Trends and Forecast 2014–2020* (2015), Deloitte Corporate Finance LLC, *Packaging Update Q1 2015* (2015), U. Reiners, *Profitability of plastic packaging* (The Third GPCA Plastics Summit, 2012)).

21 J. R. Jambeck et al., *Plastic waste inputs from land into the ocean* (Science, 13 February 2015).

22 2015-2025 projection of plastics in the ocean based on an estimated stock of 150 million tonnes in 2015 (Ocean Conservancy and McKinsey Center for Business and Environment, *Stemming the Tide* (2015)), estimated annual leakage rates of plastics into the ocean by Jambeck et al. of 8 million tonnes in 2010 and 9.1 million tonnes in 2015 (J. R. Jambeck et al., *Plastic waste inputs from land into the ocean* (Science, 2015), taken from the middle scenario), and annual growth in leakage flows of plastics into the ocean of 5% up to 2025 (conservatively taken below the 6.8% annual growth rate in ocean plastics leakage into the ocean between 2015 and 2025 as estimated in *Plastic waste inputs from land into the ocean*, middle scenario). 2025-2050 projections based on a plastics leakage into the ocean growth rate of 3.5% p.a., in line with long-term GDP growth estimates (International Energy Agency, *World Energy Outlook 2015* (2015)).

23 Ocean Conservancy, *International Coastal Cleanup* (2014). Excludes cigarette butts from calculation. D. Barnes et al., *Accumulation and fragmentation of plastic debris in global environments* (Philosophical Transactions of the Royal Society B, 2009).

24 Ocean Conservancy and McKinsey Center for Business and Environment, *Stemming the Tide: Land-based strategies for a plastic-free ocean* (2015).

25 By weight. 2015-2050 projection of plastics in the ocean as described in Endnote 22. 2015-2050 projections of fish stocks based on an estimated 812 million tonnes (Ocean Conservancy, based on S. Jennings et al., *Global-scale predictions of community and ecosystem properties from simple ecological theory* (Proceedings of the Royal Society, 2008)). The stock of fish is assumed to stay constant

between 2015 and 2050 (a conservative assumption given that fish stocks could decline as a result of overfishing).

26 Ocean Conservancy and McKinsey Center for Business and Environment, *Stemming the Tide: Land-based strategies for a plastic-free ocean* (2015).

27 United Nations Environment Programme, *Valuing Plastic: The Business Case for Measuring, Managing and Disclosing Plastic Use in the Consumer Goods Industry* (2014).

28 European Commission, Directorate General for Environment, website, *Our Oceans, Seas and Coasts: 10: Marine Litter* (http://ec.europa.eu/environment/marine/good-environmental-status/descriptor-10/index_en.htm). Based on exchange rate of EUR 1 to USD 1.10 (10 December 2015).

29 Project MainStream calculation based on data from International Energy Agency (IEA), *CO_2 emissions from fuel combustion* (2014). It assumes that half of plastics industry CO_2 emissions are generated through fuel combustion and that, of the other half used as feedstock, 15% generates CO_2 emissions through incineration. Does not include CO_2 emissions from the use of (dry) natural gas or the generation of electricity used to run the processes involved in plastic production.

30 United Nations Environment Programme, *Valuing Plastic: The Business Case for Measuring, Managing and Disclosing Plastic Use in the Consumer Goods Industry* (2014).

31 J. Hopewell et al., *Plastics recycling: Challenges and opportunities* (Philosophical Transactions of the Royal Society B, 2009).

32 M. Patel, *Cumulative Energy Demand and Cumulative CO_2 Emissions for Products of the Organic Chemical Industry* (Energy, 2003).

33 The discussion here is on direct CO_2 emissions and does not include indirect emissions (those associated with the generation of any electricity used in the manufacturing process). It also does not consider the full life-cycle emissions, which include, for example, those related to the extraction, refining and transportation of the plastic feedstock.

34 This does not consider a potential shift towards combustion in a business-as-usual scenario (in the case that landfilling is becoming less popular), which would result in a higher share of the carbon budget in 2050. On the other hand, the share of the carbon budget in 2050 could be lowered, if energy input for production shifts towards more renewable sources.

35 International agreement to limit global warming to no more than 2°C by 2100 compared to pre-industrial levels was reached at the COP16 of the UNFCCC in 2010 at Cancun (see http://unfccc.int/key_steps/cancun_agreements/items/6132.php) and reinforced at COP21 in Paris in 2015. The assumption is that CO_2 emissions from plastics will increase at 3.8% annually 2013–2030 and at 3.5% annually 2030–2050 (source: ICIS and International Energy Agency, *World Energy Outlook 2015* (2015)). A further assumption is that the proportion of oil used as plastics feedstock (3%) incinerated annually will increase from 15% in 2015 to 20% in 2050 under business as usual. Including plastics incineration in total combustion emissions is supported by the inclusion of municipal waste as a fuel in total CO_2 emissions from fuel combustion (International Energy Agency, *CO2 Emissions from Fuel Combustion*, 2015, and *IPCC Guidelines for National Greenhouse Gas Inventories*, 2006). The carbon budget for CO2 from fuel combustion is set with reference to the IEA 450 scenario (consistent with 2°C) CO_2 emissions from fuel combustion as set out in International Energy Agency, *World Energy Outlook 2015*, and to the total CO_2 budget of 1,075 Gt CO_2 as described in Carbon Tracker Initiative, *Unburnable Carbon 2013: Wasted capital and stranded assets* (2013).

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ABOUT THE ELLEN MACARTHUR FOUNDATION

The Ellen MacArthur Foundation was established in 2010 with the aim of accelerating the transition to the circular economy. Since its creation the Foundation has emerged as a global thought leader, establishing circular economy on the agenda of decision-makers across business, government and academia. The Foundation's work focuses on four interlinking areas:

Education — Inspiring learners to rethink the future through the circular economy framework

The Foundation is creating a global teaching and learning platform built around the circular economy framework, working in both formal and informal education. With an emphasis on online learning, the Foundation provides cutting-edge insights and content to support circular economy education and the systems thinking required to accelerate a transition. Our formal education work includes comprehensive Higher Education programmes with partners in Europe, the US, India, China and South America, international curriculum development with schools and colleges, and corporate capacity building programmes. In the informal education arena our work includes Re-thinking Progress, an open house educational event, and the Disruptive Innovation Festival, a global online opportunity to explore the changing economy and how best to respond to it.

Business and Government — Catalysing circular innovation and creating the conditions for it to flourish

Since its launch, the Foundation has emphasised the real-world relevance of its activities and understands that business innovation sits at the heart of any transition to the circular economy. The Foundation works with Global Partners (Cisco, Google, H&M, Intesa Sanpaolo, Kingfisher, Philips, Renault, and Unilever) to develop circular business initiatives and to address challenges to implementing them. In 2013, with the support of its Global Partners, it created the first dedicated circular economy innovation programme, the Circular Economy 100. Programme members comprise industry-leading corporations, emerging innovators (SMEs), affiliate networks, government authorities, regions and cities. The CE100 provides a unique forum for building circular capabilities, addressing common barriers to progress, understanding the necessary enabling conditions, and piloting circular practices in a collaborative environment.

Insight and Analysis — Providing robust evidence about the benefits of the transition

The Foundation works to quantify the economic potential of the circular model and to develop approaches for capturing this value. Our insight and analysis feed into a growing body of economic reports highlighting the rationale for an accelerated transition towards the circular economy, and exploring the potential benefits across different stakeholders and sectors. The Foundation believes the circular economy is an evolving framework, and continues to widen its understanding by working with international experts including key thinkers and leading academics.

Communications — Engaging a global audience around the circular economy

The Foundation communicates cutting edge ideas and insight through its circular economy research, reports, case studies and books disseminated through its publications arm. It uses new and relevant digital media to reach audiences who can accelerate the transition, globally. In addition, the Foundation aggregates, curates, and makes knowledge accessible through **circulatenews.org**, an online location dedicated to providing up-to-date news and unique insight on the circular economy and related subjects.

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