A Circular Economy of Plastics

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A Circular Economy of Plastics

A vision for redesigning plastics value chains

beyond the obvious

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PREFACE

WE LIVE IN A WORLD WHERE plastics are everywhere. There is no doubt that plastics are a versatile material for many applications across sectors and are a key material for both developed and developing societies. They keep our food fresh, and they protect us from injuries in traffic or sports. Plastics even ensure quality life through many medical applications. At the same time, plastic waste is accumulating and polluting the environment and can have harmful effects on human health and well-being, animals and livelihoods. In addition, currently 98 % of plastics worldwide are fossil-based. Only 2 % are based on renewable raw materials. In addition to the emissions intensive life cycle of plastics, this leads to substantial greenhouse gas emissions and contributes to climate change.

A general ban of plastics is obviously not realistic solution. But how can we tackle plastic pollution, greenhouse gas emissions and maintain the societal benefits that plastics offer for developed and emerging societies at the same time? The short answer is through a circular economy of plastics.

This VTT paper will present a vision of the circular plastics economy and address the requirements that allow the change from a linear to a sustainable circular economy. The focus of the paper is on the following elements:

- Design for circularity
- Circular business models
- Different recycling technologies and their benefits
- Replacing fossil resources with renewable raw materials and energy

Many of the described technical solutions already exist, with different degrees of technological readiness. However, it is very clear that real change can only be achieved through a systemic approach that addresses socioeconomic and regulatory aspects. Consumer acceptance and societies are an essential part of this change.

This document has been developed in a working group comprising VTT's top experts in the field of polymer design, plastics processing, product development, recycling technologies and circular and bioeconomy. The work has been carried out through cross-disciplinary workshops and person-to-person brainstorming sessions.

The authors thank all the contributors for their time and dedication.

CONTENTS

GLOSSARY

Fossil Feedstock

Feedstock based on crude oil or gas. Fossil feedstock is considered non-renewable, and contributes significantly to greenhouse gas emissions.

Renewable Feedstock

Renewable feedstock is based on biomass (e.g. forest) or carbon dioxide capture from industrial processes or the atmosphere. It will replenish the fraction depleted by usage and consumption in a human time scale.

Bio-Based Plastics

Bio-based plastics are based on renewable bio-based raw materials.

Biodegradable Plastics

Biodegradation is defined as decomposition of plastics by microorganisms, such as bacteria, fungi or other biological activity. The process of biodegradation is complex and involves a number of stages. Complete biodegradation yields carbon dioxide and water (and methane in the case of anaerobic conditions). The rate of biodegradation is affected by multiple factors such as light, water, oxygen and temperature. It is also important to distinguish biodegradation from the term polymer degradation. Polymer degradation is more general and is typically used in the context of any break-up of the polymeric chains through external factors (chemicals, light, heat, shear forces, etc.). Sometimes polymer degradation and depolymerisation (see below) are used in the same context.

CO_2-e

Carbon dioxide equivalence is a measure of the global warming potential (GWP) of a gas mixture expressed as the amount of carbon dioxide that would cause the same global warming effect. The CO_2-e for a given gas mixture is calculated by multiplying the mass and the GWP of the gas.

Compostable Plastics

Composting is a human-initiated degradation process under defined and controlled process conditions. Industrial composters support rapid breakdown of certain biodegradable polymer chains.

Extrusion

Plastics extrusion is a process in which raw plastics in the form of granules, flakes or powders are melted and formed into the desired shape. The main elements are a polymer and additive feed section, a screw with heaters and a die. Many different applications can be formed: films, sheets, pipes, etc. Extrusion coating to add polymeric surfaces to paper and cardboard sheets, or reactive extrusion, are also commonly used technologies in the plastics conversion industry.

Open Loop Recycling

Open loop recycling is a process in which the product is recycled into lower value applications than the original, also known as downcycling. This could be, for example, the use of mechanically recycled polyolefins from food packaging applications for water buckets. In most cases, this goes hand-in-hand with a value loss, although not necessary always the case. The use of recycled PET from drinking bottles for textiles is open loop recycling without a significant value loss

Closed Loop Recycling

In closed loop recycling, products are recycled into the same application or an application with similar value. For example, mechanically recycled PET from drinking bottles is used for producing drinking bottles again. Closed loop recycling is generally perceived as the preferred recycling option, without value loss.

Reuse

In the case of reuse, an item is used again, either for the original use or for a different purpose, without destroying the material itself. Reuse can be further improved through repair or refurbishment technologies. Examples of reuse models are bottle deposit or refill systems.

Recycling (Mechanical and Chemical)

Plastics recycling means the use of the building blocks as feedstock for new plastic products. This is done on different levels: Mechanical recycling means that the article is destroyed but the polymeric building blocks and hence the material properties are kept intact. Through thermal reprocessing, the polymer chains are recycled again into plastics. In chemical recycling the polymeric backbone of the plastics is also destroyed and only smaller building blocks are recovered. These can be monomers or other molecules that can be transformed back into polymeric materials through chemical reactions. Chemical recycling covers a wide range of processes from depolymerisation (see below) to thermochemical recycling as pyrolysis and gasification (see below).

Recyclate

A recyclate is the re-processed plastic product based on recycled feedstock. Typically, it is used in the context of mechanical recycling, in which the recycled plastic waste is re-processed into granulate and finished goods. However, the term can also be used for plastics that are based on chemically recycled building blocks.

Depolymerisation

Depolymerisation is the reverse process of polymerisation. In theory, all polymers can be depolymerised. However, due to energetic considerations, it is only feasible for polymers with heteroatoms in the polymer chain.

Pyrolysis

Pyrolysis involves using heat and anoxic conditions to break down plastic waste into compounds composed of smaller molecules, yielding a liquid or waxy mixture as well as gases. Pyrolysis allows plastics to be recycled even when the plastic waste consists of different types of plastic or composites, or contains other organic or inorganic materials or impurities

Gasification

Gasification is a technology that uses solid or liquid raw materials to make gaseous products suitable for further processing or for other uses. The reaction gases can also be selected according to the desired end product, so the reaction gas may be air, steam, oxygen or a mixture of these. In certain special cases, other reaction gases can be used, such as carbon dioxide.

Micro- and Nanoplastics

Micro- and nanoplastics can be categorised by their source into primary and secondary plastic particles as well as direct and indirect sources. Primary micro- and nanoplastics are manufactured plastic particles and exist in for example waterborne paints, cosmetics, medical applications, coatings and adhesives. Secondary particles are micro- and nanoplastics particles which are formed via breakdown of larger plastic fragments. Microplastics measure between 1 micrometre and 5 millimetres. Nanoplastics measure in the range of 1 to 1000 nanometres.

Heteroatoms

A polymer chain typically consists of carbon – carbon bonds. Heteroatoms such as oxygen or nitrogen are present in certain polymer types. Polymers with heteroatoms are more suited for depolymerisation than those without.

Fischer-Tropsch Synthesis

A chemical process that uses hydrogen and carbon monoxide for the synthesis of alkanes and ultimately fuel. The feedstock for the FT synthesis can originate from gasification of solid plastic waste streams.

ABBREVIATIONS

GHG
Greenhouse Gases

CCU
Carbon Capture and Utilization

CAPEX
CAPital EXpenditure

PS
Polystyrene

PMMA
Poly (methyl methacrylate) or acrylic glass, plexiglass

PA-6
Polyamide 6 or Nylon 6

PO
Polyolefins

PP
Polypropylene (a polyolefin)

PE
Polyethylene (a polyolefin)

1

THE NEED FOR CHANGE IN THE CURRENT PLASTICS ECONOMY AND VTT'S CONTRIBUTION

THE DRIVER FOR us to write this vision paper are the issues evident in all in our everyday lives: plastic waste in the environment and concern over the role of plastics in climate change. Yet we use and benefit from plastics every day, at home, office or school, in our hobbies or on the move. Plastic waste is accumulating in the environment due to improper waste management and is causing much harm. Furthermore, plastics contribute to climate change during several stages of their life cycle, e.g. during manufacturing, end-of-life management by incineration and even as pollutants in the environment as the waste begins to degrade. The current greenhouse gas (GHG) emissions from plastics life-cycles threaten our ability to meet global climate targets. Today, the GHG emissions from plastic production and incineration are more than 850 million metric tons, which is equal to the emissions from 189 (500 MW) coal power plants and very close to the total emissions of greenhouse gases in Germany in 2019 (858 Mt)[1]. With the current trajectory, by 2050 the cumulative emissions of the plastic life cycle will be over 56 gigatonnes CO_2-e, which is 10–13 % of the global carbon budget calculated based on the 1.5 °C target.[2]

The gap between where we are today and where we want to be with respect to minimizing plastic pollution and mitigating climate change is big. As plastic production is expected to increase three- to fourfold by 2050, the time to fix the problems is now. We need radical new approaches, with technologies across the value chain, to support the transformation of industry and societies. Our ambition is to see innovation and cutting-edge technologies transform the linear plastics economy to a sustainable circular plastics economy. This vision for a circular economy of plastics provides solutions that we believe in and want to develop further collaboratively. We invite all interested parties and stakeholders to join forces and begin the conversation on how can we best achieve circular plastics economy and how we can go beyond that.

As plastic production is expected to increase three- to fourfold by 2050, the time to fix the problem is now

To further highlight the urgency of initiating a sustainable change, the global population increase and especially the global middle-class increase is strongly linked to the growing plastic demand. It is crucial to meet these demands better than modern societies have done so far. Megacities face challenges with waste management, but on the other hand they also act as efficient platforms for circular business models such as servitizing products and different reuse models. For example, Airbnb, which did not even exist 15 years ago, is now the largest accommodation provider and still does not own any real estate. Circular economy creates new business opportunities and its societal effects are immense: the circular plastics economy is expected to create 200 000 new jobs across the EU by 2030[3].

There is immense pressure to evolve from the current polluting ways, and the regulatory framework is quickly changing and tightening. Ambitious policy measures and targets have been set – for example, the European Union (EU) has set a climate-neutral target for 2050 and the European Climate Law is set to follow the Paris Agreement goals of keeping the global temperature increase well below 2 °C and even to 1.5 °C. The European Green Deal is the roadmap for making the EU's economy sustainable and has been set up to support the aim of becoming the first climate-neutral continent by addressing the climate change and environmental degradation challenges and decoupling economic growth from resource use. The EU has published a European Strategy for Plastics in a Circular Economy to protect Europe's citizens and the environment. Via rules and regulations, the Plastics Strategy will support higher recycling rates and better waste collection systems. Furthermore, the Plastics Strategy addresses matters such as single-use plastics, microplastics and the consumption of plastic bags under the Plastic Bags Directive. The EU Waste Framework Directive has set ambitious recycling targets for plastic packaging: 55 % by 2025, 60 % by 2030 and 65 % by 2035. Companies and foundations have also set out ambitious targets, e.g. 100 % recyclable, compostable or reusable plastic packaging by 2025 in the Ellen MacArthur Foundation, a Line in the Sand Commitment. The Circular Plastics Alliance has set a goal that by 2025, 10 million tonnes of recycled plastics would be available at the markets.

Our vision is to stop plastics pollution and to make the plastics value chain climate neutral by establishing material circularity, while maintaining material performance and economic feasibility of plastics. Figure 1 depicts our vision and roadmap to transform the current status. The tools to transform the linear economy and decouple economic growth from resource consumption are eco-design and circular business models such as reuse. The technological solutions to stop plastic pollution are intelligent plastic waste collection and separation systems, repair and refurbishment, and different recycling technologies to accommodate the material and product requirements of plastics. Renewable energy sources and renewable carbon-based feedstock (recyclates, bio-based and CO_2-based) as well as alternatives to plastics will significantly reduce the impact on climate change.

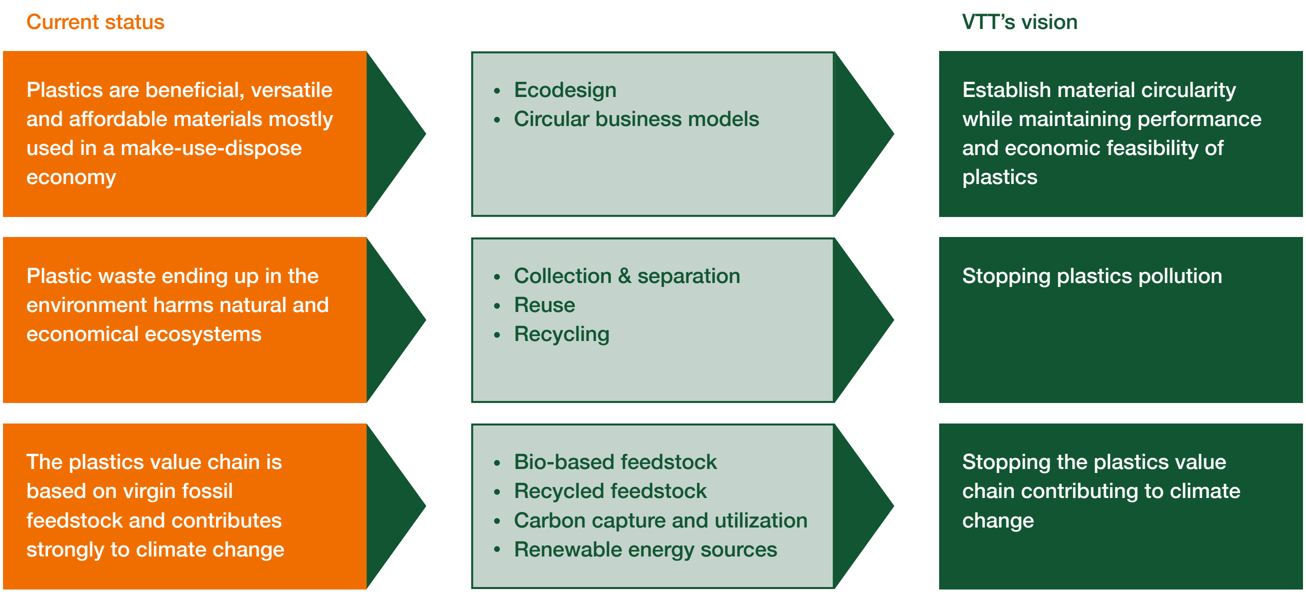


Figure 1. VTT's vision and roadmap for creating a circular economy for plastics

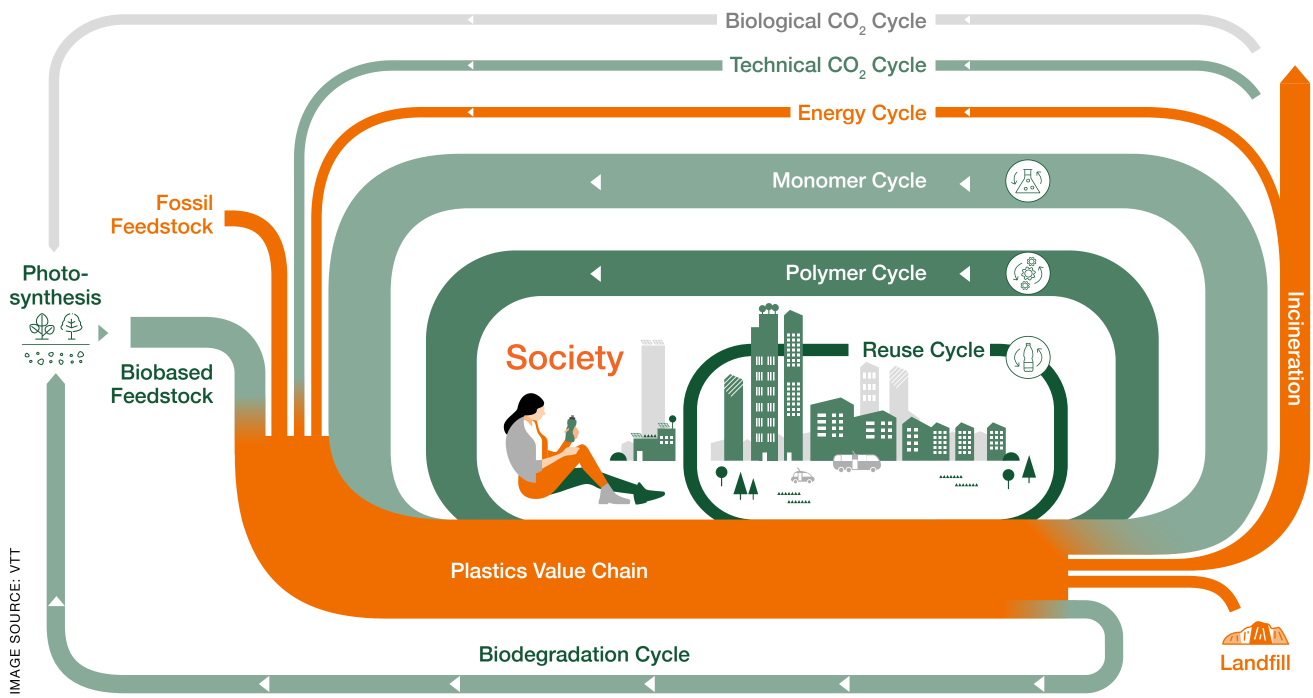


Figure 2. Overview of VTT's vision for circularity of plastics

To realize our vision for a circular economy, we follow several options to create circularity as shown in Figure 2. The current status of the plastics economy is displayed in orange color. The green cycles show how we can achieve circularity by different cycles:

- Reuse cycle: product or article level
- Polymer cycle: macromolecular level
- Monomer cycle: building-block level
- Biological cycle: biodegradation to soil
- Biological carbon cycle: biodegradation to carbon dioxide and methane
- Technical carbon cycle: capture of CO_2
- Energy cycle: recovery of the energy

This vision paper will go through the technological solutions to realize these cycles. The complexity of the plastics value chain with manifold processes and applications has the consequence that there is no ONE-FITS-ALL technology or solution for a circular plastics economy. It is important to note that this vision paper does not focus on the shift to renewable energy or energy sources and it does not address the economics of circularity. The focus is on fixing the material-related issues within the plastics value chain, which is estimated to be about half of the carbon neutrality challenge and is the key to solving the plastics pollution issue.

There is no ONE-FITS-ALL technology or solution for a circular plastics economy

2

PLASTICS – AN EXCELLENT MATERIAL IN A PROBLEMATIC MAKE-USE-DISPOSE ECONOMY

HITHERTO, PLASTICS HAVE been designed for optimum product performance in a linear economy – they have been designed for single-use and low-cost production and not for circularity. In many parts of the world, plastic waste is not well managed. The inadequate management of plastic waste has resulted in it leaking into the environment, causing environmental, societal and economic harm. Additionally, the linear plastics value chain also has significant GHG emissions, which contribute to climate change. However, plastics are undeniably beneficial, versatile and affordable materials, and the most used materials in the world.

Mass production of plastics began in the 1950s and is growing exponentially. In 1960, the annual rate of plastic production was approximately 15 million tonnes worldwide. By 2019, this figure had risen to 380 million tonnes, and the forecast for 2050 is more than 800, even up to 1200 million tonnes. Figure 3 shows plastics volume development in the world.[4]

Plastics consist of long chain-like structural components – polymers – and various additives. A specific characteristic of most plastics is that the material can be shaped using heat and pressure, greatly simplifying the mass production of different applications. Plastics are named according to the polymers they contain, although they typically contain other ingredients in addition to the polymer. The polymer is processed and mixed with additives to help with processing or improve product performance. Plasticizers, flame retardants, antioxidants, acid scavengers, light and heat stabilizers, lubricants, pigments, antistatic agents, slip agents and thermal stabilizers are examples of such substances. These additives can have significant health and safety implications and can also create technical challenges during the recycling processes, e.g. equipment corrosion.

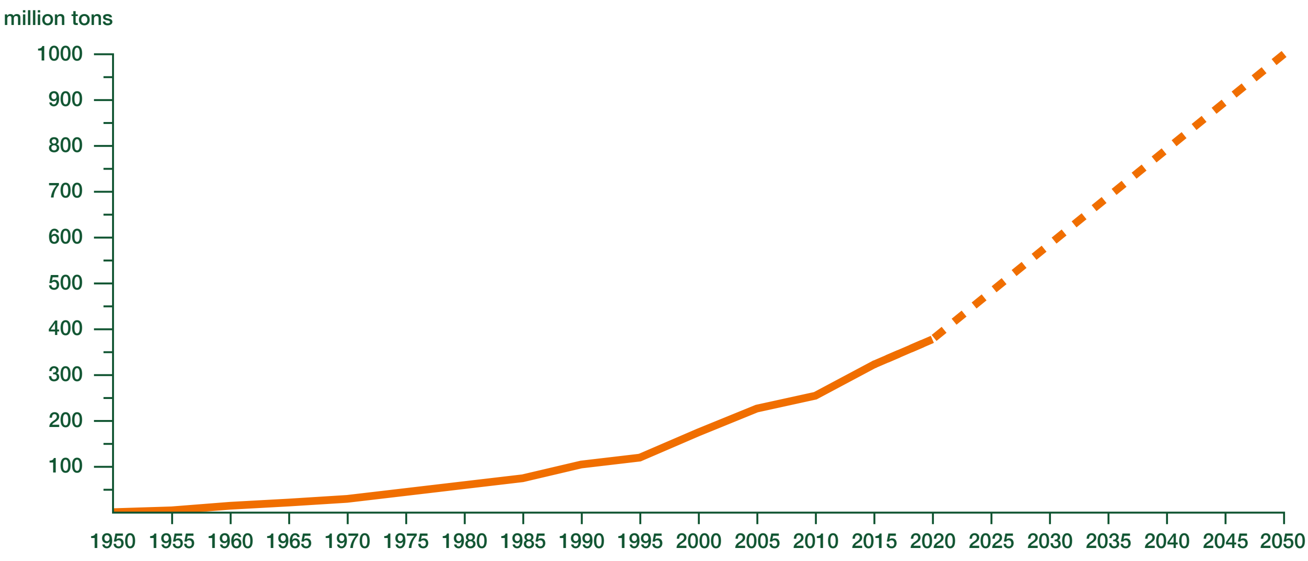


Figure 3. Global plastics volume development, 1950–2050

Currently, polymers are mainly produced from fossil sources such as crude oil. However, recycled or renewable raw materials such as biomass or carbon dioxide will become even more important feedstock streams for future plastics (Figure 4).

There are thousands of different types of plastics, but the six commodity plastics account for 70% of total global production[5]. As an example for recycling systems, these six plastic types are separately labelled. Specialty and bio-based plastics are categorized as “7 Other” (Figure 5).

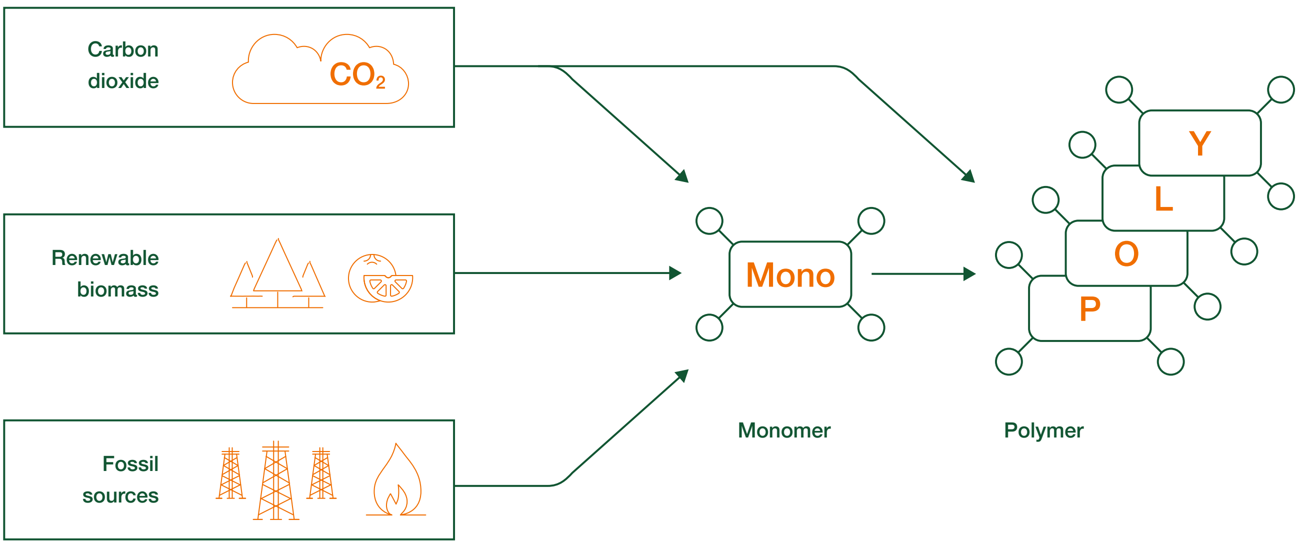


Figure 4. Raw material streams for polymers

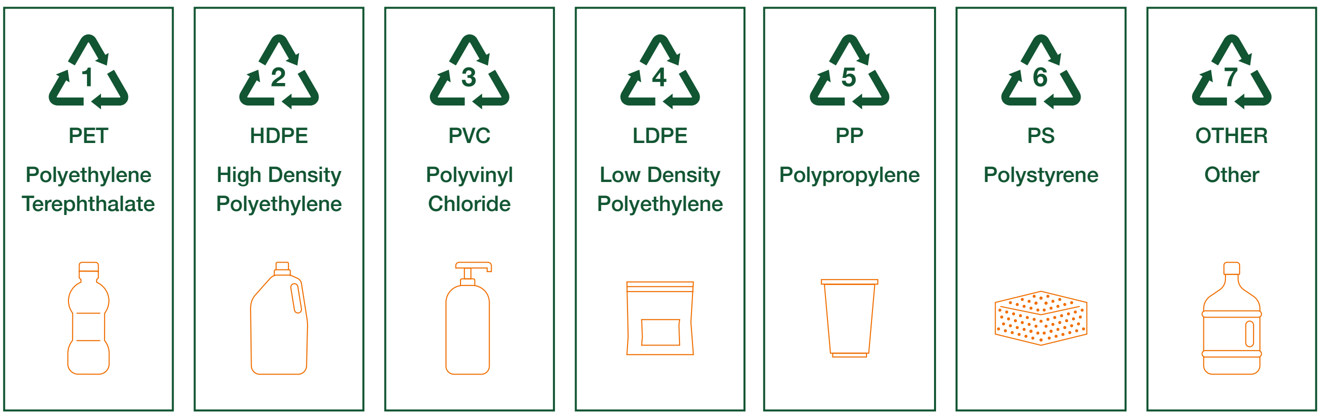


Figure 5. An example of recycle codes used for plastic packaging

Plastics are used in many applications as food packaging, drinking bottles, caps and closures, pipes, automotive parts, agricultural films, window frames, paints and wall coverings, cable insulation, optical fibres, eyeglasses, touch screens, medical implants, membranes, toys, clothes and shoes, building insulations, mattresses, etc. The main application sectors for plastics in Europe are[5]:

1. Packaging (40 %)
2. Buildings and Construction (20 %)
3. Mobility (10 %)

Food packaging is an important application as it reduces food waste by preserving and protecting the food. Food waste is already a major concern because of its direct contribution to climate change. A study by Zero Waste Scotland calculated that in 2016, the carbon footprint of food waste from Scottish households was almost three times that of plastic waste collected[6]. Food waste would significantly increase without proper packaging. In Figure 6, some examples are further presented in order to highlight the impact of plastic packaging on the shelf life of different food products[7].

In the medical sector, high performance plastics play a major role and are used in a wide variety of essential applications: prostheses, hearing aids, implants, sutures, syringes, blood bags, and so on. It is difficult to imagine a functional medical service without these assets.

In the mobility and automotive sector, plastic components weigh 50 % less than similar components made from other materials, which means a 25 to 35 % improvement in fuel economy[5]. Plastics offer lightweight solutions that fulfil essential safety requirements such as fire safety and personal protection. In the electrical and electronics sector, plastics offer safety as insulation and as a protective material.

Produce	Cucumber	Zucchini slices	Banana (distribution)	Cherries	Pear	Fish	Cheese	(Whole) Chicken
Shelf life: no packaging	3 days	1–2 days	15 days	14 days	7–10	7 days	190 days	7 days
with plastic packaging	14 days	4–5 days	36 days	28 days	22–25	12 days	280 days	20 days
Difference	**11 days**	**2–4 days**	**21 days**	**14 days**	**15 days**	**5 days**	**90 days**	**13 days**

Figure 6. Comparison of the shelf life of different food products with and without plastic packaging

3

DECOUPLING ECONOMIC GROWTH FROM RESOURCE CONSUMPTION: ECODESIGN AND CIRCULAR BUSINESS MODELS

ORIGINALLY, LINEAR ECONOMIES were developed without a recycling capacity, resulting in our environment becoming a waste reservoir. The circular economy concept facilitates elimination of waste and decouples wealth from excess consumption of resources. Regulations affect businesses through limits and restrictions on the use of certain materials or applications such as single-use plastics. Targets for recycled content in products are also increased. To ensure future compliance within the regulatory framework, plastics need to be redesigned and coupled with innovative circular business models.

Linear economies were developed without a recycling capacity, resulting in our environment becoming a waste reservoir

Although circularity by design should be considered in all steps of the value chain, it is most prominent in the stage of material and product design. Ecodesign of plastics should include the minimisation of all environmental impacts by integrating life cycle thinking into product design. It is fundamental to preventing the formation of future waste and avoiding the transfer of pollution, toxins and waste into another cycle, and to assessing the potential to reduce the material content and to replace materials or substances problematical for recycling.

For example, high-performance food packaging often consists of multiple complex layers of different polymeric materials (multilayer materials). These layers are often difficult or even impossible to separate, which makes them difficult to recycle. If heterogeneous plastic mixtures are recycled without proper separation, the recyclate is of low value. Furthermore, the use of harmful or even toxic additives makes safe recycling very difficult.

GOING BEYOND

Material Design in the Age of Digitalization

Circular plastic materials require new polymer design. The new design must support circular business models via robustness, ease of recycling through decreased material complexity and proper end-of-life management through e.g. controlled degradation. Material and product design by experimentation is slow and expensive. Digitalization helps to design materials suitable for a circular economy and to shorten the development cycle and reduce development costs.

Digitalization helps to design materials suitable for a circular economy and to shorten the development cycle and reduce development costs

VTT's own Integrated Computational Materials Engineering platform tool PropErTuneTM includes multiple models to predict the effects of process conditions on the structure-property relationships of the material and performance in use. This allows us to link material models at multiple length scales with virtual material testing and virtual prototyping. This in turn facilitates smart material selection for given applications.

This tool is multipurposed: it can be used to build and take apart materials and products. It can be used to develop materials with certain properties, for example designing the required polymer structure to get optimal barrier properties, to design durable materials for reuse, or to design materials that can easily be recycled. Furthermore, it can also be used to model and predict the degradation and fragmentation behaviour of plastics. This helps in the understanding of the formation of microplastics and also in the design of biodegradable materials. The overall impacts are beneficial for the environment, as the tool can be used for circularity design, but also economical as it brings savings to the development process of new materials, as well as for example optimizing material choices for different reuse applications.

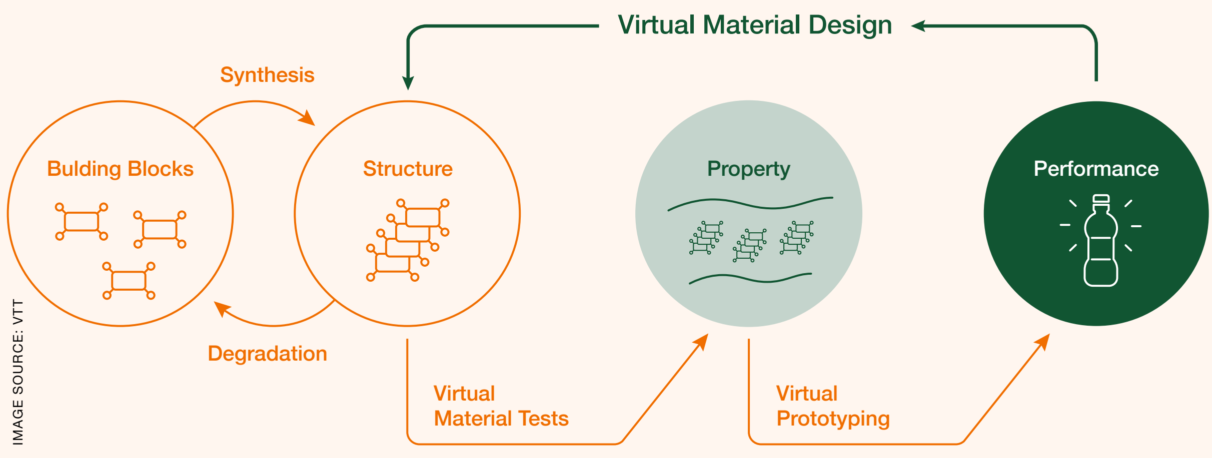


Figure 7. Virtual Material Design

Reuse is not a new concept – back in the old days it was common practice, but since the mid-20th century and rapid development of societies, linear economy has become the norm. Circular economy has now brought back reuse business models and servitizing. Moving from single-use to reuse models is at the core of a circular economy of plastics and is predicted to have a substantial impact. Reuse business models can reduce the amount of plastic used by sharing and keeping it longer in circulation. However, reuse business models are still just emerging, for example less than 3% of the “New Plastics Economy” signatories’ packaging is currently reusable.[8]

Reuse business models can reduce the amount of plastic used by sharing and keeping it longer in circulation

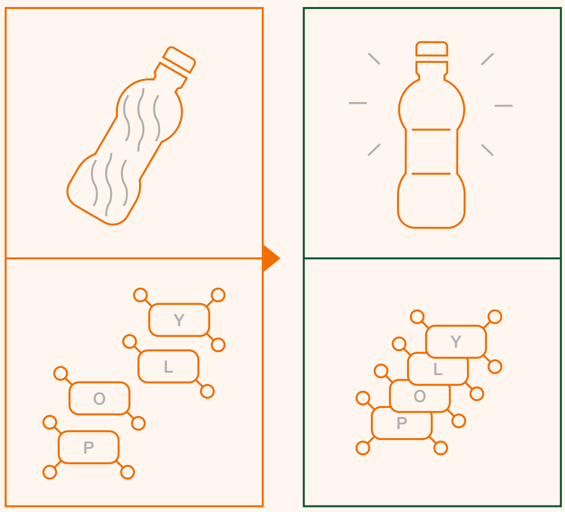
About half of the plastics produced is used in packaging, in which the life cycle is less than three years. However, only a few plastics items and packaging materials are designed to be easily recyclable. The Ellen MacArthur Foundation has estimated that without fundamental redesign and innovation, about 30% of plastic packaging will never be reused or recycled.[3] It is estimated that there is an over 10 billion USD innovation opportunity in replacing 20% of single-use plastic packaging with reusable plastics.[9]

GOING BEYOND

The Self-Healing Surface

Reuse models belong to the preferred solutions within a circular economy. However, the articles often suffer from wear and tear in the use phase. This makes the product less attractive than a shiny new one. On the molecular level, this means that the polymer chains are broken and mechanical and other properties deteriorate, which could compromise efficient and safe use of the reuse products. The degradation is eventually unavoidable and requires molecular weight recovery or repair steps before the next reuse phase. Already now we have technologies that can repair polymer chains. How about applying this technology to a deposit bottle system, where at the return station the bottle is not only collected, but also repaired? Molecular repair technologies strongly support and create new opportunities for reuse business models.

Molecular repair technologies strongly support and create new opportunities for reuse business models



A circular economy of plastics is not defined exclusively by higher recycling rates, as suggested by the EU Circular Economy legislation. To measure added value in a circular economy, it is important to consider measures of resource efficiency and circularity throughout the whole product lifecycle and the related environmental impact. In addition, the overall environmental impact and the creation of economic value need to be carefully understood before attempting to realise an effective cascading of materials or even a closed loop approach in the technical and biological cycles.[10]

4

STOPPING PLASTIC POLLUTION

THE MAKE-USE-UNCONTROLLED dispose economy of plastics has resulted in plastic waste leaking into nature and polluting the environment – humans, animals and living organisms on land and in the sea are susceptible to the effects of plastic waste in nature. Globally, 1.5–4% of global plastics production ends up in the ocean annually. The estimated release of microplastics in the environment in the EU is 75 000–300 000 tonnes each year [11]. The economic viability of agriculture, fishery and other livelihoods is vulnerable due to the effects of plastic waste.

Our technology vision to address plastic pollution is shown in Figure 8. In the traditional linear value chain, shown in orange color, plastics are based on fossil raw materials and run through manufacturing and use stages to end up in landfill or incineration, depending on the region of the world. Achieving circularity for plastics is a complex undertaking. As already mentioned before, there is no one-fits-all solution. Individual approaches for different plastic types, applications and waste streams are required to avoid mixing recyclates and take into account plastics degradation and subsequent value loss. The elements of plastics circularity are manifold. The reuse cycle has been discussed already and requires the plastic products integrity to be maintained. The macromolecular integrity is maintained in mechanical recycling while in the chemical recycling loop, the building blocks are broken down to smaller molecules that are used as recycled feedstock for plastics. Furthermore, carbon dioxide can be captured and used as a renewable feedstock. Biodegradation is another route to avoid formation of waste. The target is to maximize circularity as much as possible and optimize the flows in the different cycles.

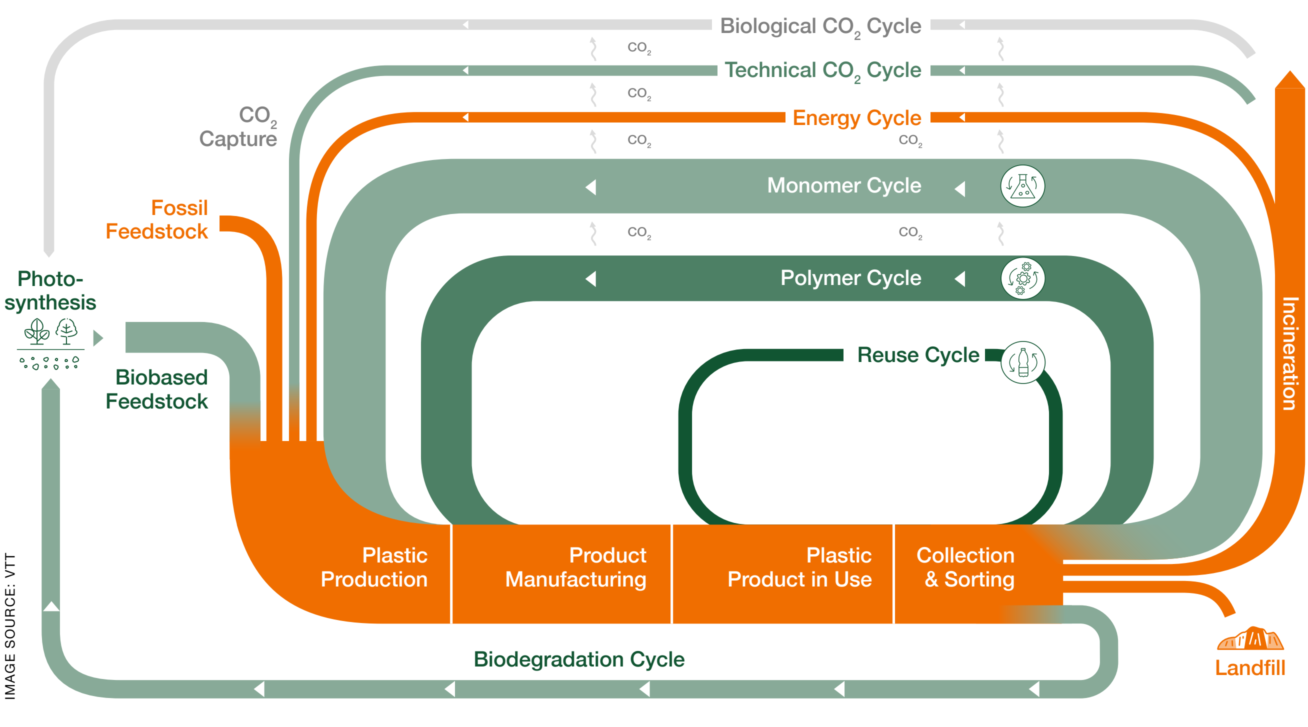


Figure 8. VTT's technology vision for circular plastics

The Micro- and Nanoplastics Challenge

The macro-sized plastic waste is further fragmented into micro- (0.1–5 mm) and nanoplastics (1–1000 nm). This is a recent cause of concern due to the unknown effects such as mechanical irritation and exposure to chemicals, as the fragmented particles can transport possibly harmful substances with them. Apart from the fragmentation of larger plastic parts, there are also direct feeds of micro- and nanoparticles into the environment. It has been estimated that 30 % of ocean plastics are micro- and nanoplastics. In marine environments, these particles have been associated with harming fish and other marine organisms, causing lower growth, reproduction and well-being and affecting biodiversity.

Micro- and nanoplastics can be categorised into primary and secondary plastic particles. Primary micro- and nanoplastics are manufactured plastic particles and exist in for example paints, cosmetics, medical applications, coating, and adhesives. Secondary particles are micro- and nanoplastics formed via breakdown of larger plastic fragments. These are more challenging to control, as they come from several different direct and indirect sources such as fishing nets, plastic packaging waste, cigarette filters, cleaning and personal care products, car tires, synthetic textiles and their washing, agricultural plastic applications, irrigation, sewage sludges – the list goes on.

GOING BEYOND

Removing Micro- and Nanoplastics from Waste Water

It is crucial to establish globally functioning collection and recycling systems and to increase recycling rates in order to stop waste leakage and further pollution of the environment. One batch of laundry from a washing machine can release more than 1 million microfibres into the waste water, eventually ending up in the open waters if not caught. For washing machines, filters are already on the market to trap microplastics, but how do we catch and remove nanoplastics? We envision coagulants to remove micro- and nanoplastics that could be used in many applications varying from washing detergent to waste water treatment plants.

The following sections will examine these circular elements in detail.

4.1. SORTING AND SEPARATION OF PLASTIC WASTE

After collection, plastic waste is separated and pretreated before the actual recycling process. Plastic properties are very much defined by polymer type and its molecular weight. If different plastic types are mixed during recycling, the value of the recyclate is often lost. Therefore, it is essential that plastic types are carefully separated before reprocessing. Plastics can be identified on the basis of physical properties, spectroscopy or visual inspection. Separation at recycling sites is typically handled manually or automated based on optical identification. However, these technologies have limitations, mainly due to high error margins.

Plastics containing high loads of harmful additives, such as brominated flame retardants and phthalates, are not currently analysed with optical sensor systems. Therefore, future development in sorting and separation will move to unique markings of plastics that are easily recognized online and will go well beyond the material type. These markings will contain information on additives, application and any other information that is relevant for re-processing.

GOING BEYOND

Seeing Below the Surface

Identifying additives in plastics broadens the range of recyclable plastics and has the potential to increase the recycling rates significantly. This will be useful especially with plastics containing halogenated compounds such as bromine (flame retardants) in electronics, electrical equipment, furniture, vehicles and construction. These additives are essential for safe product use, but limit the recycling possibilities immensely due to regulations restricting the use of these substances in new products. Furthermore, these substances are hazardous in vapour, liquid and dust form. Currently, the recycling centres analyse the halogenated content of batches from samples offline.

Online identification and removal of harmful substances to increase safety and value

Online identification and efficient sorting based on harmful additive concentrations, even below a few percent, is an interesting business opportunity for recyclers, as more plastics can be recycled and higher value can be achieved. Improved identification will contribute to reaching the plastic waste recycling target set in the EU: 55 % by 2030. It also has the potential to decrease the amount of plastic waste ending up in incineration and hence to decrease the carbon footprint and enhance material circularity.

4.2. MECHANICAL RECYCLING – IMPROVING RECYCLATE QUALITY AND INCREASING RECYCLING RATES

Mechanical recycling is currently the main technology for the recycling industry and focuses on thermal re-processing of waste plastics to recyclates. Mechanical recycling implies that, although the actual product is destroyed, the molecular integrity of the plastic is retained. However, thermal reprocessing causes material degradation and the effect is already significant after a few extrusion cycles. Mechanical recycling is a preferred choice for well-separated and clean plastic waste streams in order to provide the highest value and best possible quality for recyclates.

GOING BEYOND

Counteracting Decrease in Recyclate Quality During Mechanical Recycling: Infinite Recyclates

Thermal reprocessing has a strong degradation effect on plastic. If not counteracted, only a few recycling loops are practically feasible before the plastics lose their mechanical properties and the possibility for use of recyclates in similar value applications is lost. However, we already have concepts to fix broken polymer chains and create new chain connections.

Figure 9 depicts the process steps from waste collection, sorting, pretreatment, actual reprocessing and recyclate valorization. The smart reprocessing is carried out in a two-extruder set-up. The melt flow behaviour of the recyclate is measured after the first extruder and the viscosity after the second extruder. Smart control algorithms adjust the feed of virgin polymer, polymer chain repair agents and compatibilizers before the second extruder in order to counteract the detrimental effects of feedstock quality variations and polymer degradation.

Applying polymer chain repair and new chain connections in the mechanical recycling process and combining them with the adaptive feed control developed by VTT will increase the recyclate quality significantly, as well as the recycling rates, and bring us closer to infinite circularity.

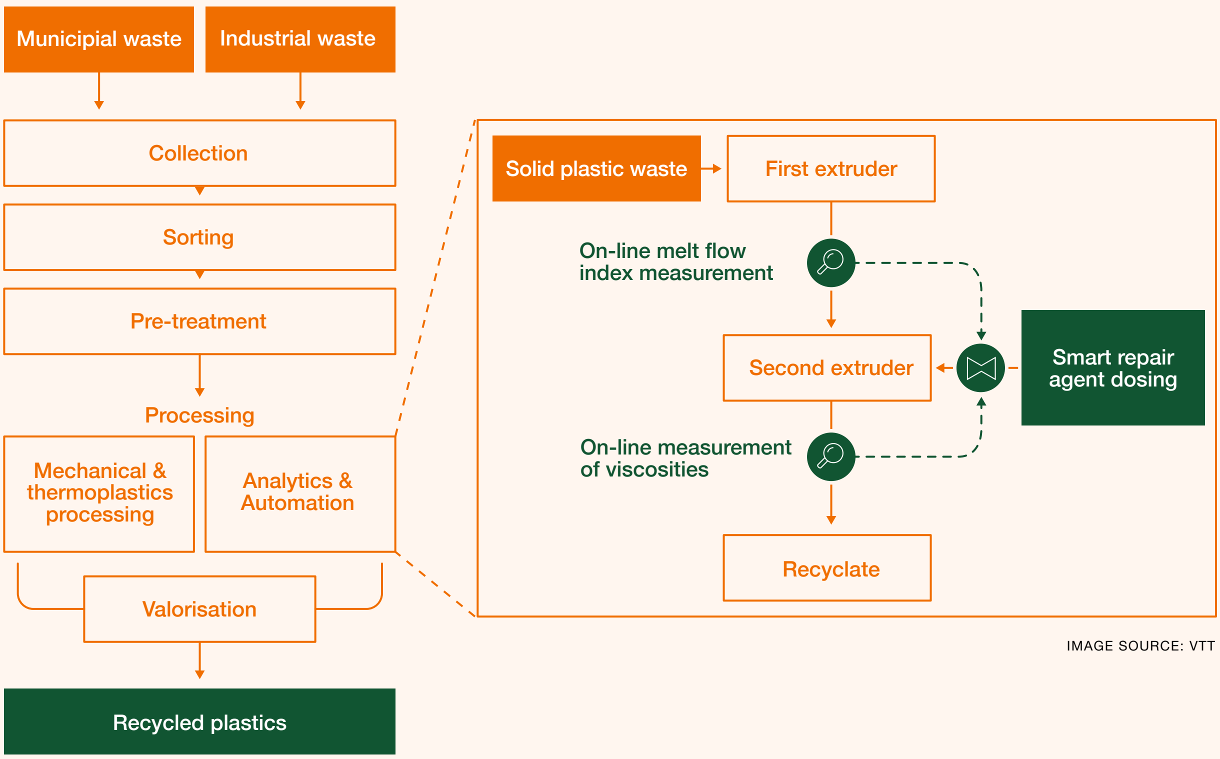


IMAGE SOURCE: VTT

Figure 9. Smart Mechanical Recycling Scheme

GOING BEYOND

Turning the Varying Feedstock Challenge into an Opportunity

The main challenges in mechanical recycling are varying feedstock quality and polymer degradation. Feedstock quality variations are mainly due to inefficient sorting and separation of polymer types. It is a generally accepted perception that recyclates based on mixed plastics are of low value. Available studies confirm that this perception is generally correct. However, there are also indications that certain combinations do not dramatically decrease the plastics performance[12]. Part of the problem is caused by non-miscible fractions of different polymers. We envision that through the smart use of compatibilizers, the effects can be mitigated and value created for previously worthless recyclates. Furthermore, certain combinations and plastic reprocessing side streams can improve the properties of recyclates.

4.3. CHEMICAL RECYCLING TECHNOLOGIES TO TREAT CHALLENGING PLASTIC WASTE FRACTIONS

Many of the plastic waste streams that are not suitable for mechanical recycling, for example due to complex multi-material products or contaminants, can be recycled chemically. Chemical recycling typically implies breaking of the polymer chains and it can be achieved by several different technologies. It should be taken into consideration that chemical recycling is rather energy and/or chemical intensive processing if compared to mechanical recycling processes.

Chemical recycling is not yet applied in industrial scale, due to the lack of a constant and affordable feedstock supply as well as unclear legislation. In Europe in 2017, over 5 million tonnes of plastic waste was mechanically recycled and only around 50 000 tonnes was chemically recycled. In our vision, chemical recycling will increase the overall recycling rates significantly and will be complementary to mechanical recycling, as it includes plastic waste streams that are not suitable for mechanical recycling. We foresee that eventually up to one third of all plastic waste will be suitable for chemical recycling.

In our vision, chemical recycling will increase the overall recycling rates significantly and will be complementary to mechanical recycling

It is important to assess the net benefit when selecting the ecologically and economically most suitable route for plastics circularity.

For some plastics, waste incineration can be the most feasible end-of-life option. It is possible that plastics containing harmful substances can be burnt in incinerators, if the incinerator is able to remove the harmful substances from the smoke gases. Many plastics have a good heat value, making them good inputs for waste-to-energy plants.

4.3.1. SOLVOLYSIS AND DEPOLYMERIZATION

Solvent-based recycling covers a wide range of techniques. It includes technologies in which plastics are dissolved in sub- or supercritical solvents. The main benefit is efficient removal of harmful substances from the plastics without destroying the polymer chain. This technology is currently still limited to certain plastic types, e.g. polystyrene, and strictly speaking it is not chemical recycling as the polymer chain remains intact. Some refer to it as physical recycling.

Solvents can also be used for depolymerisation: in these processes the plastics are not only dissolved, but the polymer chain is also broken down or depolymerized. The general rule is that condensation polymers, such as nylon and polyesters, are easier to depolymerise than polymers without heteroatoms in the chain. The reaction products are usually monomers that can be re-polymerized, or other useful chemicals.

Although this approach is an elegant way to recover clean polymer building blocks, it is practically limited to a small fraction of the plastic waste.

4.3.2. THERMOCHEMICAL RECYCLING

In contrast to many other material recycling technologies, the benefits of thermal technologies are that they are highly flexible with regard to the input streams. While the technologies are typically CAPEX intensive, the investments required to sort or clean the feedstock can be minimised. The technologies allow handling of heterogeneous mixtures, laminated packaging materials and various composite structures. In practice, thermal refinement technologies are capable of processing almost all types of plastic waste. In contrast to incineration, not only is the energy recovered, but valuable building blocks for materials are also obtained as products of thermochemical recycling processes.

Thermochemical recycling can be further divided into pyrolysis and gasification. Both technologies have already existed for decades for the conversion of other waste streams and biomass into fuels. We foresee a strong shift in thermochemical recycling of plastic wastes from conversion to fuels towards production of monomers and other valuable chemicals.

We foresee a strong shift in thermochemical recycling of plastic wastes from conversion to fuels towards production of monomers and other valuable chemicals

Although polyolefins are the most commonly used plastics, they are also difficult to recycle compared to polyesters or polyamides. However, we have evidence that thermochemical recycling of polyolefins gives good monomer recovery yields.

Pyrolysis

Pyrolysis involves using heat and anoxic conditions to break down plastic waste into compounds of smaller molecular size, yielding a liquid or waxy mixture as well as gases. Pyrolysis allows plastics to be recycled even when the plastic waste consists of different types of plastic or composites, or contains other organic or inorganic material or impurities. Any impurities are generally removed and become part of the carbonised residue of the process.

The primary output from pyrolysis is a wax or liquid oil. Pyrolysis can be implemented cost-effectively on a smaller scale than gasification, enabling a decentralised and integrated pyrolysis approach. It also allows recycling of materials that are collected in insufficient volumes for feasible mechanical recycling.

Pyrolysis can produce monomers with good yields from certain types of plastic (PS, PMMA, PA-6). Pyrolysis can use plastic inputs containing polyolefins (PP, PE) to make fuel for diesel engines, components for creating alloys or inputs for oil refineries. Catalytic pyrolysis allows the recovery of olefins from polyolefins.

Gasification

Gasification is a technology that uses solid or liquid raw materials to make gaseous products suitable for further processing or other uses. The gasification process can be implemented in different ways, such as fixed bed, fluidised bed or entrained flow gasification. The reaction gases can also be selected according to the desired end product, so the reaction gas may be air, steam, oxygen or a mixture of these. In certain special cases, other reaction gases can be used, such as carbon dioxide.

The most suitable gasification solutions for recycling plastic waste are those that yield hydrogen and carbon monoxide, which can then be used to produce various plastics or chemicals. Under certain conditions, it is possible for gasification to yield monomers directly, among other products. Impurities can be removed from the gaseous end product using gas purification, and therefore contaminated plastic waste can also be used to produce a clean raw material.

4.4. RECYCLING SOLUTIONS FOR CONTROLLED END-OF-LIFE MANAGEMENT

Biodegradation is a process in which the molecular structure of a material is broken down through the metabolic activity of microorganisms – such as bacteria, yeasts and molds. These microorganisms use organic substances as a source of carbon, oxygen, nitrogen and energy. Biodegradation can also be defined as chemical modification of materials. It is a prerequisite for processes such as composting, which is biodegradation under specific conditions. Biodegradation rate and degree should always be linked to the type of environment and the conditions. The main four biodegradation environments for polymers and plastic products are soil, aquatic, landfill and compost. All environments have different microorganisms and conditions such as temperature, moisture, pH, and available oxygen. In theory, microorganisms can biodegrade all organic materials. However, from the perspective of microorganisms, plastic waste has been in the environment too short a time for them to adapt and synthesize their polymer-specific enzymes for plastic waste degradation. This is why different biotechnical solutions have been developed to effect and control the biodegradation process, for example to depolymerise polymers.[13,14,15]

Biodegradation rate and degree should always be linked to the type of environment and the conditions

4.4.1. BIOTECHNICAL RECYCLING

Not all bio-based plastics are biodegradable. The source of the feedstock does not determine the biodegradability. The rate of biodegradation can be very slow, even so slow that the material is considered to be non-degradable. For example, biodegradable polymer can decompose within weeks in optimum conditions, whereas it may remain almost unchanged in cold seawater. We envision biotechnical solutions to enhance biodegradability and provide bio-based recycling options of plastics. The biotechnical recycling of plastics emphasises:

Not all bio-based plastics are biodegradable

1. The identification and modification of microbes or microbial flora that can break down plastics and the development of microbial recycling solutions;
2. The development of enzyme reactions specifically targeted at depolymerising plastic polymers to monomers

GOING BEYOND

Enzymes Remove Elastane from Textile Waste

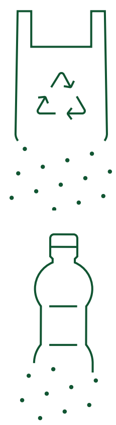
Globally in 2015, 63 % of the virgin feedstock for produced clothing was plastic-based and despite efficient collection practices in some countries, 73 % of produced clothing ended up in landfills or incineration.[16] Elastane is used with synthetic and natural fibres in textiles for its super stretchability. Elastane content in clothes varies typically between 5 and 10 %. However, elastane is causing problems in textile recycling processes, for example it tangles around screw conveyors and disturbs processes to recycle other textile materials. We envision a biotechnical solution to remove elastane as a pretreatment step from textile materials before their recycling process. This would make recycling of textiles more feasible and ensure higher recyclate quality and furthermore, contribute to the decrease of environmental impact of textiles.

4.4.2. COMPOSTING

Composting is biological degradation of organic waste under controlled conditions in a specific environment. For certain biodegradable plastics, industrial composting can be the preferred end-of-life option. However, it should be noted that biodegradable polymers should not be used as single-use materials but kept in circulation.The composting process provides high quality compost for soil remediation and fertilization. The quality of the compost depends on the materials and how they are degraded. For safety in a circular plastics economy, it is crucial to properly investigate and design the biodegradability and compostability of materials so that the composts do not contain undegraded fragments such as secondary microplastics that end up in the environment as a plastic pollutant.

The Effects of Micro- and Nanoplastics in Biodegradation

Micro- and nanoplastics are difficult to detect and remove from the environment, oceans, soils and air. As most plastics do not biodegrade, the micro- and nanoplastic pollution can remain in nature for hundreds of years, and thus begins to accumulate. Furthermore, it has been estimated that agricultural soils could hold even 4 to 23 times more microplastics than marine systems – in a kg of soil, there can be over 40,000 microplastic particles. Concentrations of polyethylene fragments in soil have been reported even up to 500 kg/ha in China, typically globally between 60–300 kg/ha.[17,18,19] Micro- and nanoplastics can originate from biodegradation residues and sludges. If the materials do not degrade properly in the composting process, the residue used for example as soil remediation material is a direct source of micro- and nanoplastics in the environment.



4.5. SUMMARY OF RECYCLING METHODS

We have already established that there is no one-fits-all solution for plastics recycling. The decision for the right recycling method is dependent on many parameters. The composition of the waste stream and ease of separation predetermine the recycling route. If the plastic waste is well sorted, mechanical recycling is the preferred choice. If not, chemical recycling is better equipped to handle mixed waste streams. Larger volumes improve the economy of recycling processes in general. Particularly thermochemical recycling economics are sensitive to the scale of operation.

The required purity of the recyclate also determines the recycling route. Pretreatments in addition to separation, such as solvent treatments and sterilization, might be required. Chemical recycling has an advantage as it typically breaks down the polymer building blocks into monomers that can be repolymerized and create basically a pure new polymer.

Finally, the targeted end product of the recyclate is of high importance. The economically best option must be assessed on a case-by-case basis. The aim is to maintain the value in closed loop recycling. However, sometimes open loop recycling, e.g. bottle PET to PET for textiles, gives the best possible value.

Table 1 shows the strengths, weaknesses and opportunities of the different recycling methods. In addition it shows VTT's offerings related to it.

	TECHNIQUES	STRENGTHS	WEAKNESSES	OPPORTUNITIES	VTT OFFERINGS
MECHANICAL RECYCLING	Sorting	Multiple methods for different materials Well established technologies	Material identification not optimal Leads to contamination and low quality recyclate	New sensor developments and digital watermarks to improve sensitivity	**available**
	Reprocessing	Established technolgies	Feedstock variation Degradation	Adaptive virgin polymer and additive feed control to overcome feedstock variations Molecular Repair	**available**
SOLVENT-BASED RECYCLING	Dissolution of plastics in sub- or supercritical fluids	Removal of harmful substances Polymer chain remains intact	Only limited applications	Usable as pre-treatment method for further recycling	
DEPOLYMERIZATION	Hydrolysis or Glycolysis are the main routes	Recovery of clean monomers or useful chemicals	Limited to polycondensates	Biotechnical solutions	**available**
THERMOCHEMICAL RECYCLING	Pyrolysis and Gasification	Can handle heterogeneous feedstock Wide, tunable product range	CAPEX intensive	Shift product slate to monomers	**available**

Table 1. Comparison of plastics recycling methods

5

MAKING THE CIRCULAR PLASTICS ECONOMY CARBON NEUTRAL

PLASTICS HAVE RATHER carbon-intensive life cycles which accelerate climate change, especially due to the fact that the vast majority of plastics are made from virgin fossil raw materials. The manufacturing of plastics requires energy intensive processing and also contributes to direct greenhouse gas emissions.[20] The production of fossil-based commodity plastics causes an average of 2.5 tonnes of CO_2 emissions for every tonne of plastic produced. Furthermore, incinerating, landfilling, recycling and composting processes also release CO_2.[20] The carbon present in 1 tonne of plastic materials corresponds to approximately 2.7 tonnes of carbon dioxide, which is released when the material is incinerated or completely degraded.

The future circular plastics economy will rely on bio-based feedstock, carbon capture and utilization and recycled plastics

The industries need secure, affordable and functional feedstock for their production, which makes it challenging to decouple from virgin fossil resources. Yet the sustainability megatrend and the environmental problems linked to plastics and the plastics industry are driving change in future feedstocks. The future circular plastics economy will rely on sustainable raw materials: bio-based feedstock, carbon capture and utilization technology (CCU) based polymers and recycled plastics. The recycled plastics will mainly initially originate from the fossil-based sources, but also eventually from recycled bio-based and CCU-based polymers.

In a circular economy, the recycling of existing plastic materials is an important source for renewable carbon. However, it is clear that only recycling the fossil-based polymers will not be able to provide the lion's share of renewable carbon in a sustainable manner in the near future.[21] It is evident that the growth of plastics production cannot be met sustainably if the raw material base is not widened. McKinsey has estimated that 50 % of plastics worldwide could be reused or recycled by 2030. This means that by 2030, up to almost one third of plastics demand could be covered by production based on previously used plastics rather than from virgin fossil feedstock. This estimate is based on a high-adoption scenario, comprising a massive increase in mechanical recycling volumes, a take-off in pyrolysis, and oil prices at around $75 per barrel. If by 2030 the total production of plastics is doubled from today's value, taking into account McKinsey's estimate of increased recycling, the use of virgin fossil raw materials would still grow by one third. This simple calculation shows that even if the increased recycling of plastics does take place, there will still be an enormous need to use alternative raw materials, such as cellulose, starch, sugars, fats and oils, and CO_2 from the atmosphere.

5.1. BIOBASED FEEDSTOCK

Bioeconomy has an integral role in the future circular plastics economy in decreasing feedstock dependence on virgin fossil resources. Biomass utilized for bio-based plastics and plastic replacing alternatives can originate from several natural resources: biomass from agriculture and forestry, algae and marine biomass, as well as different agricultural and process side- and waste streams such as food waste, biowaste, ashes and dusts, rejects and recovered materials, etc. In some applications the plastic can be replaced, for example by foamed cellulose instead of polystyrene for package cushioning. Cellulose is an integral structural component of green plants and some algae as well, and it is the most abundant renewable resource in the world. It is a multi-purpose material of the future for example in composites, high-performance plastics, membranes, filters and foams.

Renewable Materials in Finland

Cellulose fibre products are on the market and we all know and use them. On top of that there are new innovative materials under development. The innovation pipeline includes materials such as thermoplastic cellulose and nanocellulose.

One of the most significant properties of packaging manufactured from wood fibre is its recyclability. The same fibre may be recycled from one product to another four to seven times until it becomes shorter and its technical characteristics disappear. Eventually, the fibre becomes a valuable biofuel. Carbon remains bound in the product for as long as the fibre is in circulation.

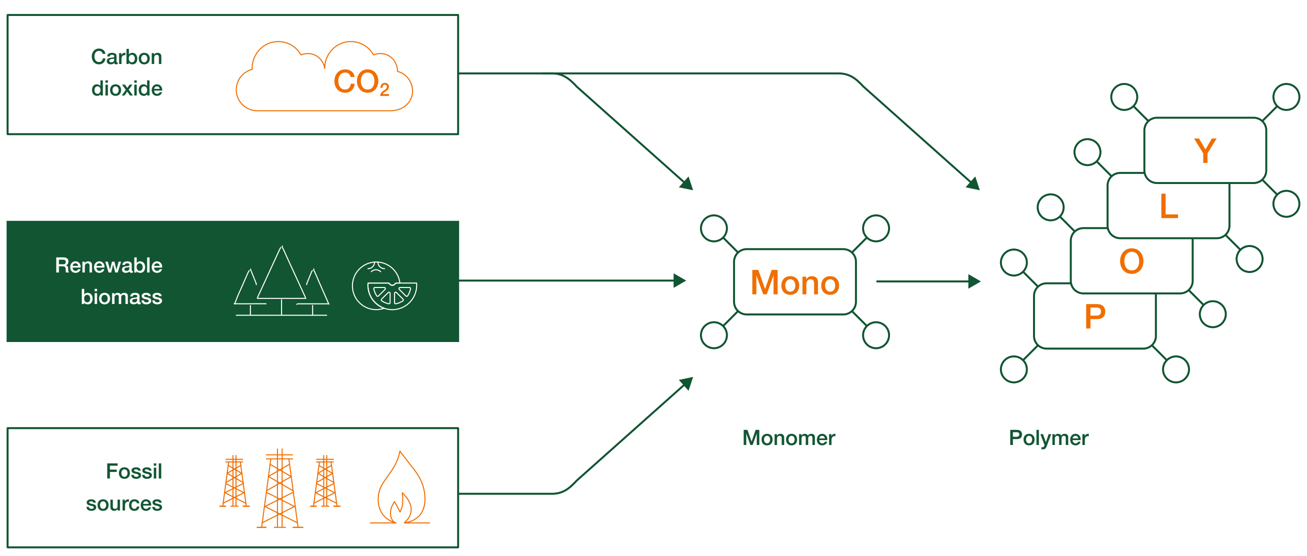


Figure 10. Utilizing Renewable Biomass for Plastics Manufacturing

5.2. CARBON DIOXIDE AS FEEDSTOCK

Turning CO_2 from the cause of climate change into a valuable raw material is an important part of the future circular plastics economy. CO_2 can also be a valuable intermediate for monomer manufacturing. The challenge is to capture CO_2 from the atmosphere, industrial processes and degradation processes. Technologies for this do exist, but need further development to be economically feasible[22]. We envision CO_2 to be an essential building block of the carbon reuse economy. Some polymers can be directly synthesized from CO_2, e.g. polyurethanes and polycarbonates. Carbon Capture and Utilization (CCU) also has many other applications. In the context of plastics, CCU in combination with Fischer-Tropsch synthesis yields synthetic naphtha. Synthetic naphtha can be further converted to polymers, as is already now done with fossil naphtha.

Turning CO_2 from the cause of climate change into a valuable raw material is an important part of the future circular plastics economy

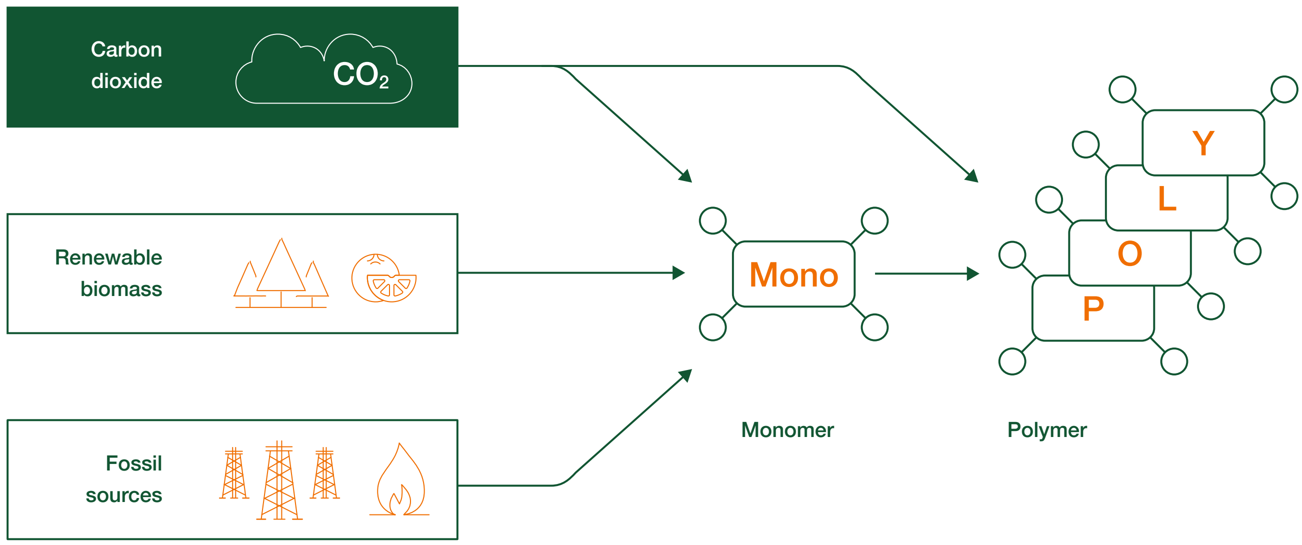


Figure 11. Utilizing Carbon Dioxide for Plastics Manufacturing

6

CONCLUSION AND OUTLOOK FOR A CIRCULAR PLASTICS ECONOMY

WE HAVE DEMONSTRATED that there is no alternative to a circular plastics economy if we want to combine a healthy and safe lifestyle with a sustainable way of living. But it is also very clear that there is no silver bullet for the very complex transition to a circular economy of plastics. The best solution (technical, ecological and economical) must often be evaluated in a case-by-case scenario. There is a variety of technologically feasible solutions across the value chain; sometimes a reuse model is preferred, sometimes mechanical recycling offers the best option, and in other cases thermochemical recycling is the way to go. Technologies are complementing each other and lifecycle analyses must be used to assess the best feasibility.

A key element to stop plastics pollution is to establish globally functioning plastic waste management systems and expand the market demand for recycled plastics. Therefore, we need to further increase the efficiency of plastics recycling and improve the recyclate quality. We highlighted the paramount importance of efficient sorting and separation in mechanical recycling, as mixed waste and polymer degradation are responsible for value loss. We foresee that smart dosing of additives in the mechanical recycling will counteract this loss and thereby increase the profitability of recyclates. The same repair technologies will be applied for improving material lifetime in reuse business models, thereby decreasing the lifecycle greenhouse gas emissions of plastics.

Waste streams that cannot be mechanically recycled will be handled in chemical recycling. The products will be further tuned towards monomers and refinery feedstock and thereby increase recycling rates significantly and contribute to overall carbon neutrality.

Furthermore, it is obvious that renewable carbon is the feedstock for a sustainable plastics economy. Renewable carbon covers recycled plastics feedstock, bio-based materials and carbon dioxide. However, it must be very clear that the recycling industry's high energy requirements should also be fully covered by renewable energies in order to prevent the release of additional fossil CO_2. Carbon Capture und Utilization (CCU) processes are in development and will provide renewable feedstock-based products and thereby mitigate climate change.

Ecodesign will support the transition to a circular economy and is a key factor in decreasing future plastic waste. The redesigned materials and products are optimized for use, reuse and recycling. We foresee significant time and cost savings in this transition through material design by modeling platforms. Redesigning future plastics is one of the key elements in stopping plastics pollution and mitigating climate change.

Novel circular business models and changes in regulations are needed in order to support a sustainable transition towards circularity. To accelerate the transformation of the industry, and of both developed and developing societies, we need new approaches with technologies and innovative business models across the plastics value chain. Our vision is to stop plastic pollution and make the plastics value chain climate neutral by establishing material circularity, while maintaining material performance and economic feasibility of plastics. Our ambition is to see innovation and cutting-edge technologies as key elements in establishing this. We wish to highlight that even though the challenges faced are immense, they can be overcome. We at VTT will continue our work in research, development and innovation in the circular plastics field and call for collaboration to start creating the much-needed sustainable circular economy together today.

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