White paper

From #plasticfree to future-proof plastics

How to use plastics in a circular economy

June 2023

TNO innovation for life

Fraunhofer UMSICHT

Authors

Dr. Esther van den Beuken
Dr. Jan Harm Urbanus
Dr. Paul Stegmann
Toon van Harmelen MSc
Dr. Tom Ligthart

Dipl.-Ing. Jürgen Bertling
Dr.-Ing. Stephan Kabasci
Anna Schulte MSc

Coordinators

Dr. Esther van den Beuken

Prof. Dr.-Ing. Manfred Renner

Contents

Chapter 1
Introduction

Jürgen Bertling finds it difficult to decide on the most environmentally friendly way to consume bottled water.

Plastics are shrouded in controversial debates. While manufacturers have been highlighting the benefits of plastics for decades, there are more and more stakeholders demanding a complete refuse, referring to the environmental problems associated with the use of plastic. Neither the thesis that continuing with the unlimited use of plastics is feasible, nor its antithesis of radical renunciation appear to be a reasonable or even feasible path from a scientific perspective.

In the Hegelian sense, science needs to reach a synthesis of thesis and antithesis and show a new, sustainable way of designing and using plastics. However, this will not be limited to minor adjustments, but also require radical changes or even abandonment of previous values, production schemes and usage practices. Transforming plastics production and use is a complex, dialectical challenge that must consider the integration of stakeholder perspectives, the balancing of their values, and the potential of current and future technologies. This report is an attempt to do so.

'Refuse' is promoted as the first circular economy strategy to decrease primary resource consumption and lower emission levels. Refusing a material follows the mindset: "What does not have to be produced and put onto the market does not have to be reused, recycled and recovered". We can refuse plastics, but we cannot refuse all the products we need in our daily lives.

Thus, replacing plastics with alternative materials is a widely promoted consumer trend, for instance in packaging, where paper, glass, metal, and/or new reusable (non-)plastic products are promoted as more sustainable alternatives. The hashtag #plasticfree with more than 4.7 million posts on Instagram is one example for this trend that promotes products or practices refusing plastics and replacing them with other materials.

However, plastics also have their benefits due to their unique properties as light-weighted, versatile, and cheap materials with high barrier properties. Moreover, alternative materials and products can have inferior product properties and they also have their environmental impacts, which can be worse than the ones of plastics (see Sections 2.2 and 2.3). Nevertheless, the drawbacks of our current plastic usage – fossil resources depletion, plastic leakages into the environment, including microplastics formation, and greenhouse gas emissions - are no longer acceptable and ask for a change.

The main goal of this paper is to explore how a future–proof, circular, and sustainable plastics economy should look like. To do so, we need to address manifold questions, such as: In which applications can plastics be refused or replaced? How do plastics need to be designed, (re-)used and recycled in the future to take advantage of their benefits while solving their drawbacks?

Chapter 2 highlights the drawbacks and the benefits of plastics use compared to alternative materials. Chapter 3 introduces a vision of a sustainable and circular future plastics economy and proposes a roadmap to achieve this vision. The concluding Chapter 4 shows how Fraunhofer and TNO plan to contribute to the development of this visionary future.

Chapter 2
The benefits and drawbacks of using plastics

Esther van den Beuken shows her beloved repair tool - a plastic sewing machine.

2.1 The drawbacks of plastics today

Plastics have the fastest growing production of all bulk materials globally[1,2]. Without changes in current plastic consumption patterns, projections expect a doubling[3,4] (see Figure 1[4]) or even quadrupling[5] of plastic production until 2050. Such growth would also drastically increase the already existing environmental and health impacts of plastics and the use of resources.

2.1.1 Climate impact

The plastics sector is currently responsible for 4.5% of the global Greenhouse-gas (GHG) emissions[6]. Taking the previously described increases in production and consumption as a basis, without a change in energy supply to the plastics industry, the GHG impact of plastics could also double[4] or even quadruple until 2050[5]. 61% of the plastics life-cycle GHG-emissions can be attributed to plastic resin production and 30% to the conversion of the plastics into products. The end-of-life causes 9% of the GHG emissions, with incineration holding the biggest share[5].

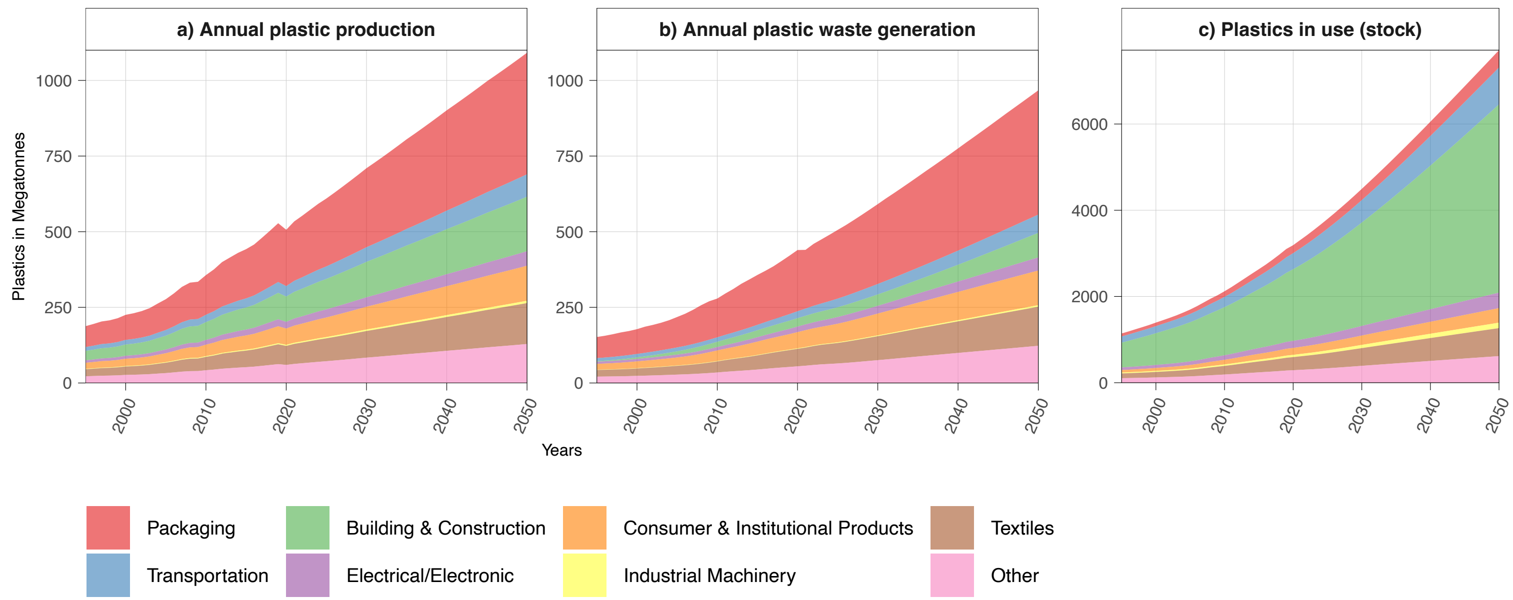


Figure 1. Projections of Global plastic production, waste generation and plastic stocks by sector (Adapted from Stegmann et al 2022[4]).

2.1.2 Environmental and health impacts

Littering & microplastics: Plastics are lost to the environment during production, use and their end of life. Microplastics, fragments smaller than 5 mm, can form through wear and tear, while larger plastics can get lost due to littering or improper waste management practices. Globally, an estimated 0.8 million metric tonnes (Mt) of microplastics and 9.5 Mt of macroplastics entered the environment in 2017, representing a 2.4% loss to the environment when compared to the 432 Mt plastics produced that year[7]. Based on exposure to UV, chemicals and temperature, degradation rates of plastics vary from a few years to over thousand years[8,9]. Microplastics can result in human and ecological health impacts[10,11,12]. Especially through air, micro and nanosized plastics can enter human lungs and the blood stream[11]. However, there is still limited scientific evidence on adverse human health impacts of micro- and nanoplastics, due to data limitations and inconsistent assessment methods[13]. Nevertheless, plastic emissions have become one of the major environmental concerns among laymen and topic-experienced persons[14].

Particulate matter (PM) emissions during production: The PM health footprint of plastics rose by 70% since 1995, causing the loss of 2.2 million disability-adjusted life years (DALY)[6]. In 2015, plastics were responsible for 2.8% of the global health impact of PM emissions[6].

Human toxicity: Some monomers and additives used in plastics may leach inside the human body and affect human health, such as bisphenol A (BPA) and phthalates[15]. However, a robust evidence base on human health effects of plastics and their relation to exposure concentrations is currently lacking[16].

2.1.3 Resource depletion and import dependency

The growing plastics sector consumes a considerable amount of fossil raw materials as feedstock or process energy. The chemical sector with plastics as a major output (ca. 40% in weight[17]) is the largest industrial energy consumer[2]. The IEA expects that the chemicals & plastics sector will be responsible for nearly half of the global growth in oil demand until 2050[2].

Next to the climate impact of fossil raw materials use, this growing resource consumption also causes supply problems and reduces the sovereignty of countries. Since the beginning of 2021, the plastics industry has been suffering from supply problems that have become increasingly widespread, both regarding feedstocks (oil and natural gas) as well as intermediate products needed for plastics production.

The European Commission has issued and regularly updates a list of the foreseen critical raw materials characterised by high economic importance and a high supply risk[18]. Among them are materials that are used as catalysts or flame retardants in plastics production, such as antimony, vanadium, or platinum[19].

The plastics growth outlook (see Figure 1) reveals that the climate, environmental, and health impacts of plastics in the future will likely further increase. However, refusing or replacing plastics is no easy task as they are an integral part of our economy and alternative materials cause negative environmental impacts as well.

2.2 The benefits of plastics

Plastics are a very versatile and lightweight material that can be used in a wide variety of applications. Their properties such as density, thermal diffusivity, or the Young's modulus differ considerably from other materials, especially metals and glass (see Figure 2). For example, glass is heavier in weight and more brittle. Wood and paper may exhibit similar properties in an individual category, but still have a different profile overall. In particular, the water vapour permeability, which is important for packaging, can be substantially lower with plastics than with paper.

Moreover, the properties of plastics can be changed via physical and chemical modifications (by additives, fillers, multilayer composites, foaming, crosslinking, etc.), allowing for a wide range of applications. This adaptability to the specific tasks is the strength of plastics. At the same time, however, it is also one of the reasons for the difficulties in recycling due to a lack of compatibility or the content of legacy substances.

Additionally, plastics are cheap, durable materials that have a good processability and high efficiency in manufacturing. While plastics take their toll on the environment (cf. Section 2.1), they can also offer environmental benefits by substituting heavier, less flexible, and more GHG-intensive materials like steel and concrete[2,20,21] or by extending the shelf life of food products and protecting them from contaminants[22].

It requires a case-by-case assessment to judge which materials have the lowest environmental impact in certain applications while still fulfilling the necessary functions.

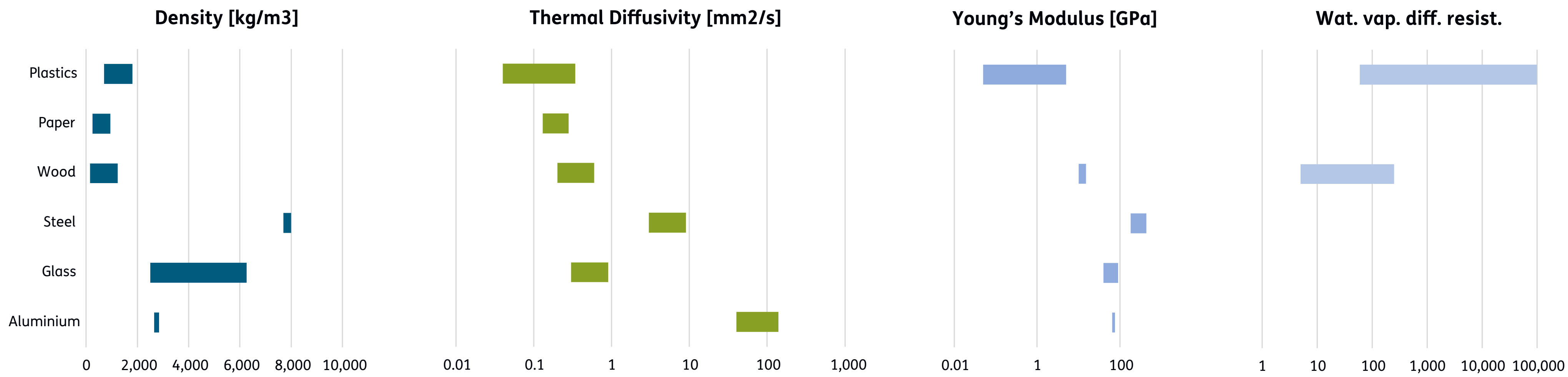


Figure 2. The properties of plastics compared to other materials (Data sources:[23,24]).

2.3 Plastics and their alternatives

This Section uses examples of different sectors to discuss the benefits and trade-offs of plastics compared to other materials.

2.3.1 Packaging

With approx. 37%, packaging has the biggest share in annual global plastic production and makes up almost half of generated plastic waste due to its short service life[1].

Plastic packaging is said to avoid food waste by increasing the shelf-life of products and reducing damage during transportation. However, evidence for a positive effect of packaging on food waste is inconclusive and needs to be assessed case by case. Globally, 40% of our food is wasted[25]. By reducing food waste, we can avoid additional food production and its related environmental impacts.

For example, a cucumber wrapped in plastic film has an almost 5 times longer shelf-life and packaging grapes reduces their in-store waste by 20%[24]. Moreover, using a foam net to cover peaches has proven to reduce the damage area ratios of non-packed peaches during transportation from 60-90% to 2.3-17.3%, depending on the transport distance[26]. However, evidence for a positive effect of packaging on food waste is inconclusive. A study by WRAP found a shelf-life extension of the product through plastic packaging for only 2 out of 10 tested cases[27].

Moreover, their research revealed no significant and consistent influence of packaging on disposal decision of customers[28]. In fact, packaged products might lead to more food waste, as selling products loose without packaging allows customers to buy the amounts they actually need[28]. Moreover, plastic packaging is also often used for aesthetic reasons or for differentiating products[29]. Statistical data from European countries show that there is no positive correlation between the amounts of plastic packaging used and food waste generated[30].

Hence, more packaging does not necessarily mean less food waste. In fact, it might even have the opposite effect. Refusing those packaging applications that do not offer environmental benefits would promise substantial demand – and consequentially emission – reduction of plastics and other materials used for packaging.

Compared to other packaging materials, plastics can offer GHG savings in production. However, it is important to also consider the end-of-life of materials. Even with higher emissions in production, a material can still be environmentally preferrable if it is reused or recycled more often, which needs to be assessed case-by-case. For example, bottles made from glass, natural fibres, steel or aluminium all emit more GHG emissions in production than plastic bottles[24]. The use of glass as an alternative for plastic packaging will likely lead to an increased environmental impact due to more material use and higher manufacturing impacts[31,32,33].

However, it is also decisive what happens at the end of life of a product, e.g., if it is a single use product or if it can be reused. A more GHG intensive material that allows for more reuse or better recycling can thus compensate for its higher emissions in production. For example, glass containers have higher emissions in production than plastic containers, but if their lifespan is more than 3.5 times longer they can outperform plastics[34]. These break-even points differ by study and application. For example, a refillable wine bottle only achieves a similar environmental performance than a bag-in-box packaging (cardboard and plastic) if it is reused around 40 times[35]. For milk, the same study showed that a single use HDPE container outperformed the refillable glass bottle in terms of environmental impact.

By making plastics packaging reusable, their environmental performance can be improved. However, potential trade-offs between different environmental impacts have to be considered. In the previous example, the best solution in terms of GHG emissions might be a reusable plastic bottle. Plastics can be used for producing reusable packaging to substitute single use packaging from cardboard, such as reusable crates for fruits and vegetables[36]. On the other hand, uncoated cardboard has the advantage of degrading in the environment, while plastics remain in the environment for decades or even hundreds of years[8]. However, coated paper or cardboard does not decompose quickly either, and must be designed in a way that does not hamper its recycling.

2.3.2 Building and Construction

The building and construction sector is the second biggest consumer of plastics with around 16%[1]. Moreover, the sector might even cover more than 50% of the plastic stock in use due to their long product lifetimes, see Figure 1c. In buildings, plastics are used amongst others for insulation, damp proofing, window frames, roofing, flooring, and service installations such as pipes, but also in paints, waxes or glues[37].

For plastics used in building and construction alternatives do exist, but these may not always have a better environmental performance[38]. For example, wooden and aluminium window frames are alternatives to PVC frames. However, wooden frames require more maintenance which may reduce their overall sustainability, and aluminium frames have worse insulation properties compared to PVC frames[39] which negatively affects the energy consumption for heating and cooling the building[40].

The use of insulation materials in buildings accounts for substantial energy and financial savings in the long-term[41,23]. The mainstream thermal insulations used in buildings are plastic ones such as polyurethane (PU), extruded polystyrene (XPS), expanded polystyrene (EPS), or phenolic foam, and inorganic ones such as mineral, stone or glass wool[42]. The plastic options can achieve better thermal resistance, water resistance, density, and price than inorganic options, but have a higher flammability and low recycling rates[42].

LCA studies do not reveal a clear preference for using plastics or inorganic materials for insulation: for example, LCAs showed that mineral wool has a lower environmental impact than XPS, PU, and phenolic foam, but that EPS performed better than mineral wool[41,43]. Moreover, the assessment differs per impact category, e.g., glass wool shows lower GHG emissions than XPS, but has a higher eutrophication and ozone depletion potential[44].

Novel natural, organic fibres such as fungal mycelium-based materials could replace plastics in some applications in the building & construction sector but require further development and assessments. Natural, organic fibres could provide a more sustainable alternative for insulation materials in buildings[42,44]. However, these alternatives also face challenges regarding their costs, water absorption, or flammability[42]. Mycelium-bound fibre composites are examples for novel, natural materials with tailored structural, physical, chemical, mechanical, and biological properties that could replace plastics in a wide range of applications such as floor tiles, insulation and acoustic panels[45]. Mycelium composites are bound by fungal growth using, for example, straw, hemp shives and sawdust as base materials. Initial LCAs indicate that these building materials could perform better than conventional materials in terms of GHG emissions, but worse in terms of eutrophication and land-use[46,47]. However, further assessments and technological developments of such materials are necessary to evaluate their performance and increase their use, respectively[48].

The growing use of artificial turf pitches contributes to microplastics emissions. More sustainable alternatives do exist, but further innovations are needed. Due to their intensive and year-round usability, the proportion of artificial turf pitches has increased significantly worldwide in recent years. They usually contain polymer granules made from used tire rubber, EPDM or TPE as a loose performance infill in an artificial turf carpet. Bertling et al. showed that large amounts of these infill are emitted into the environment when used during sports and due to strong winds and stormwater[49]. The authors suggest pitches without infill or with natural materials such as cork or olive pits as alternatives, which would also lower the life-cycle carbon footprint. However, also other components of the artificial turf pitches, such as the synthetic turf carpet and the cushioning layer, cause microplastics emissions and are still hardly recyclable today. Innovations are urgently needed here.

2.3.3 Transportation

Due to their light weight, plastics can save product transportation costs and emissions and reduce fuel use in cars[23]. Currently, 7% of global plastics are produced for the automotive sector[1] and the share of plastics in cars is expected to rise[50]. Particularly in the automotive sector, substituting metals with plastics lowers the weight of cars and consequentially also the emissions in the use phase[23].

Despite their low recyclability, the use of carbon fibre reinforced polymers for car bodies can reduce the environmental impact of cars over their entire life cycle, compared to conventional steel bodies[51]. However, the use of light-weighted advanced high strength steel for car bodies can also achieve similar reductions for certain car types, such as battery electric vehicles[52].

One of the most important plastic applications in the transport sector are tyres made from modified natural or synthetic rubber. Through wear and tear, tyres emit 1,327,000 t/a of particles such as microplastics in the European Union alone[53]. There are initial estimates of the particle propagation paths[54], but regarding their degradation there is hardly any current publication. Data from 1980 indicate a fairly rapid degradation time of around 500 days[55]. Tyres contain a high level of additives, so that many potentially critical substances are released into the environment together with the microplastics. For example, a reaction product of 6PPD, an antioxidant commonly used in tyres, was shown to be toxic to coho salmon[56].

Switching transport to rails would avoid emissions from tyres, next to providing other environmental benefits. However, individual transport will hardly be able to refuse the use of polymer-based tyres. Therefore, innovations are needed to minimize tyre wear without having to sacrifice safety and fuel consumption. At the same time, the pollutant content should be reduced, and the degradability should be investigated and optimized.

2.3.4 Agriculture

The use of plastics in agriculture can lead to littering, and the accumulation of microplastics in the environment. Substituting these conventional plastics with fully biodegradable plastics or alternative materials may help to reduce microplastics concentration in agricultural soils. However, the impact of alternative solutions on the product quality needs to be critically evaluated. In agriculture, plastic films, binders, clamps and other objects are used for, amongst others, storage of silage, construction of greenhouses or for mulching[57]. In bale silage or mobile silos used for feed production, the airtight seal is of great importance for proper and germ-free fermentation to preserve the feed. Attempts at film-free silaging that can be integrated into modern agricultural production had little success so far[58].

Nevertheless, strategies using biomass for silage covering, such as Sudan grass, oil radish, sowings of cereals, rapeseed or field beans, appear to be an interesting prospect. Moreover, the development of sprayable systems based on renewable raw materials that are readily degradable seems promising[59].

However, it must be critically examined whether the alternative solutions lead to disadvantages in product quality or to production losses, and how these are to be evaluated from an ecological point of view compared with a reduction of plastics emissions.

2.3.5 Textiles

In textiles, plastics – namely synthetic or polymer fibers – can offer environmental benefits compared to natural materials such as cotton, although trade-offs between different impact categories have to be considered. Clothing has the fourth biggest environmental footprint of all consumption categories in the EU[60]. Around 12% of the annual global plastics production goes into textiles[1]. Substituting cotton with acrylic or polyester (PET) yarns could reduce the environmental impact, partly because the impacts of these raw materials are lower, but also because the spinning of fibres from acryl and PET has less impact[61]. Other studies like the one published by the JRC[60] present contradicting results, showing higher climate change impacts for plastics fibres than for cotton. However, the same study shows that freshwater ecotoxicity of cotton by far exceeds that of polymer fibres.
At the same time, textiles with synthetic fibres cause microplastics emissions during washing, drying and use[62].

In the Netherlands, textiles are estimated to be the fourth biggest source of microplastics emissions after plastics in tyres, packaging, and agriculture[63]. Considering these trade-offs, a clear recommendation on the most environmentally friendly material choice in textiles still cannot be given.

2.4 Towards evidence-based material choices

Systemic assessments are needed to soundly decide where plastics use is beneficial and where it could be refused or replaced. Those assessments need to consider (a) the functional properties of a target product, (b) the comparison to alternative products without plastics, (c) their impacts in a multitude of environmental, social and economic categories, and (d) over their entire life cycle.

We conclude that plastics will and should remain an important part of our economy and our daily lives. Therefore, their use must be carefully considered, their disadvantages eliminated and their impact on the environment mitigated. TNO and Fraunhofer work together towards a sustainable, circular plastics sector. What could such a future plastics system look like, and how could we get there?

Jan Harm Urbanus feels comfortable between his multipurpose polymeric building blocks.

Chapter 3
The future plastics economy

Paul Stegmann on his daily walk to get rid of plastic waste.

We envision a future economy in which all applications are critically examined whether they can be refused, rethought or the material input reduced. For the remaining plastics applications, important improvements in product design, business models and material characteristics regarding durability, recyclability and degradability have enabled a circular economy for plastics.

Reuse, repair, refurbishing and re-manufacturing of plastic products have become integral and dominating fields of regional economic cycles. After use, all plastics products are collected and re-worked according to their state of wear. New polymers facilitate high-quality recycling. On the rare occasion of plastics ending up in the environment, these materials degrade without the release of any harmful particulates (formerly known as microplastics) or chemicals (formerly known as persistent organic pollutants). The reliance on raw material imports for plastics production in Europe is strongly reduced. All components of modern plastics: polymers, additives, fillers, reinforcements etc. are produced from recycled plastics or renewable feedstock like biomass or CO_2.

Moreover, the renewable electrification of the plastics value chain, from resource extraction and production, operation of reusable plastics items pools, to recycling of plastics, contributes to the goal of a sustainable plastics sector. Figure 3 summarizes our vision of the future plastics economy.

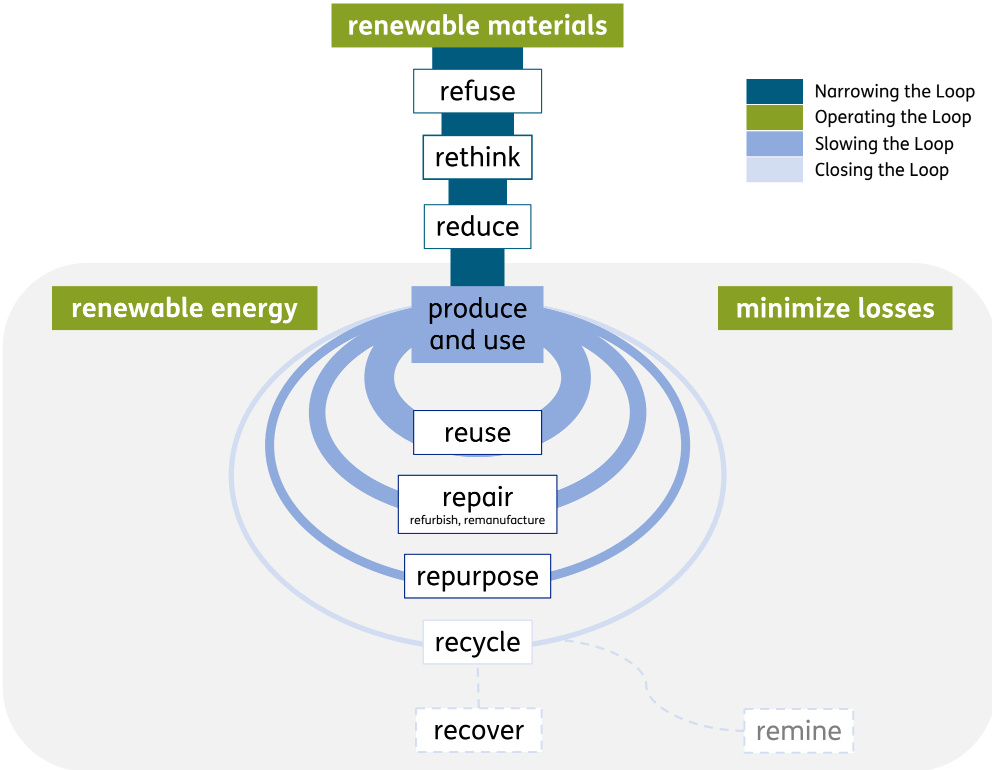
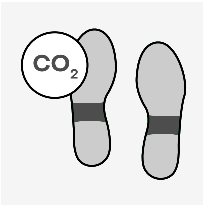


Figure 3. Vision of a future plastics economy based on limitation, circulation and renewables.

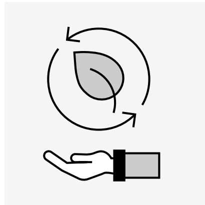
3.1 Overarching goals

We believe that plastics will still be an important class of materials in the decades to come. However, they have to be produced sustainably, maintained well during use and treated responsibly at their end-of-life in a circular economy to achieve climate neutrality[64], reach zero-pollution of ecosystems[65], and contribute to technological and socio-economic sovereignty.

Such a circular economy of plastics is not an end in itself. Even though the preceding vision sounds promising it must meet overarching sustainability goals:

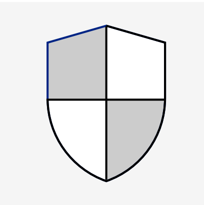


Achieve climate neutrality:
The European Union strives to achieve net-zero greenhouse gas (GHG) emissions by 2050[66]. The role of plastics in achieving climate neutrality is discussed in the European Plastics Strategy[67]. However, minimizing GHG emissions from plastics requires much more than establishing a recycling economy by eliminating landfill, incineration, and waste leakages. In line with EU's 2050 climate neutrality goal[68] and the Green Deal[69], the European Commission published in March 2022 the first package of measures for a transition towards a circular economy by 2050[70]. These include a systemic change of how plastic products are designed, produced, used, and recycled in the EU. Achieving climate neutrality requires the implementation of radical actions and changes in plastic industry looking beyond today's mechanical recycling practices and single-use plastics – 150 million metric tons of mixed plastic waste end-up as waste in the same year that they are produced[71].



Zero pollution to protect ecosystems and human health:
In parallel to achieving climate neutrality, the goal to protect ecosystems and humans is framed in the European Plastics Strategy[67]. For protecting ecosystems, a future plastics economy must aim to reduce plastics pollution and littering as well as at removing already littered plastics without harming aquatic or terrestrial ecosystems. Further goals are reducing particulate matter emissions in production and microplastic release during use. Aiming for zero plastics emissions, a long-term goal would entail the use of completely degradable plastics in all applications where losses into the environment cannot be fully avoided.

No toxic and harmful additives and polymers should enter the market and pre-existing substances of concern need to be handled with caution and should be replaced by safe alternatives as fast as possible. Safe recycling technologies need to be (further) developed to eliminate concerns that recycled materials from post-consumer waste affect human health, especially regarding plastics with food contact.



Accomplish technological sovereignty:
The concept of technological sovereignty gained momentum in the EU after the COVID-19 crisis revealed strong dependencies from third countries in strategic sectors[72]. Edler et al. defined technological sovereignty as “the ability of a state or a federation of states to provide the technologies it deems critical for its welfare, competitiveness, and ability to act, and to be able to develop these or source them from other economic areas without one-sided structural dependency”[73].

In the EU, plastics production relies heavily on the import of fossil feedstocks and other resources. At the same time, the circular economy is an approach that focuses on regional rather than global material flows, and regards already existing anthropogenic feedstocks as a source of raw materials.

Thus, a circular economy could become a cornerstone for technological sovereignty. The idea of technological sovereignty is closely linked to the idea of vulnerability, which describes the importance of a material for an organisation or country, its substitutability, and the ability to change and improve processes and products depending on that material. A switch to the reuse of plastics and the use of recyclates would be a clear contribution to sovereignty. However, it is currently limited due to technological, regulatory and financial hurdles and quality requirements; reuse-systems require large investments in infrastructure and recyclates are not yet available in the necessary quantity and quality. Today, only 16 % of plastics are recycled worldwide[74] – in the EU27+3 it is about a third[71].

3.2 Main Approaches and Strategies

Substantial changes are required to achieve a sustainable economy for plastics that solves the current drawbacks (see Chapter 2) and meets the overarching goals (see Section 3.1). Therefore, suitable strategies must be set up and actions be taken for improvement. Strategies and actions aiming at a circular economy can provide synergies but can also have adverse effects on one or more of the overarching goals or induce rebound effects. There are several classifications for describing different strategies like the historical ladder of Lansink[75], which has become well known as the Waste Hierarchy in the European Waste Framework Directive[76], or the R-Strategies by Potting et al[77].

We have expanded these strategies and grouped them into four main approaches that in our belief form the basis for a well performing and sustainable circular economy: Narrowing the Loop, Operating the Loop, Slowing the Loop and Closing the Loop (Figures 4 and 5). They are presented in detail in the following sections; their application is discussed in Section 3.3.

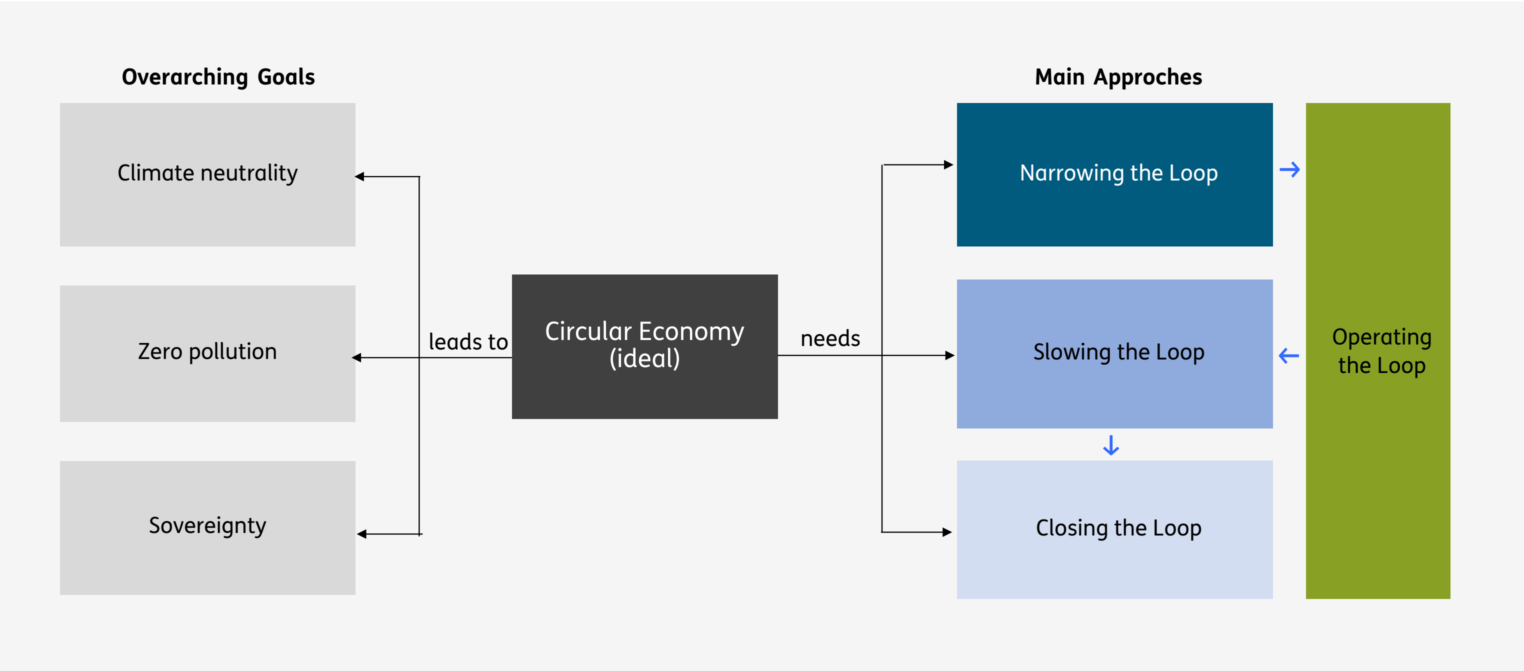


Figure 4. An ideal CE will lead to the achievement of the overarching goals while incorporating the four main approaches along the loop.

So far, discussions and widely used frameworks about how to implement a circular economy start with looking primarily at Closing the Loop. The term 'Closing the Loop' is emblazoned under the monitoring framework for the circular economy published by the European Commission[78]. Even though this framework partly addresses strategies during use, the recycling strategy and actions to close the loop at end-of-life dominate the framework. One specific aim of the European Plastic strategy is to ensure ten million tons of recycled plastics in products on the European Union market by 2025[67]. There is no comparable challenging target for slowing the loop concerning, for instance, reuse or repair. However, we encourage initial focus on Narrowing the Loop, then focus on the cross-cutting Operating the Loop before Slowing and Closing the Loop for transforming today's linear plastics economy to a circular future.

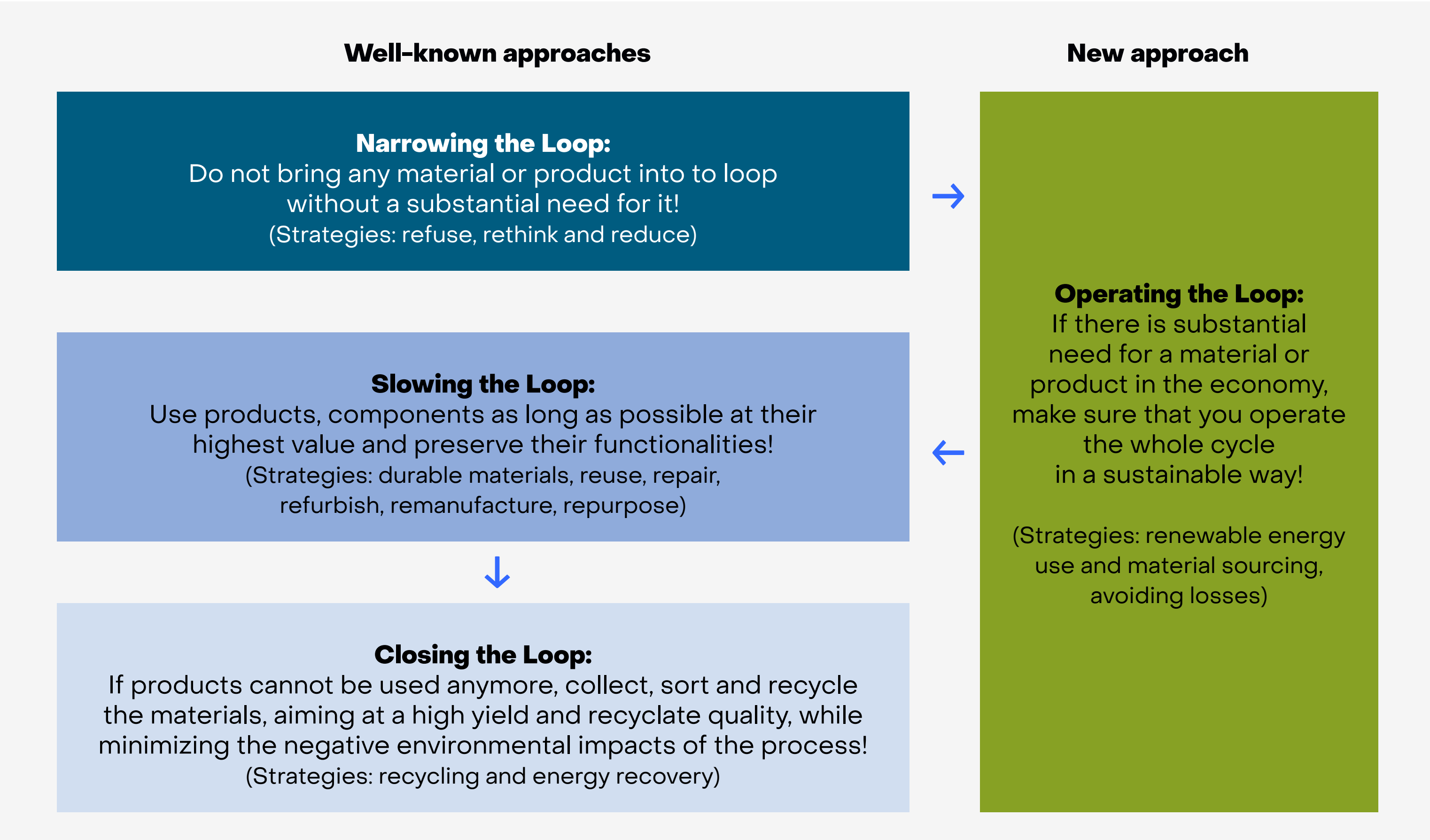


Figure 5. Detailed description of the four main approaches for a sustainable circular economy.

3.2.1 Narrowing the Loop – scaling down material use and its impacts

Narrowing the Loop attempts to reduce the quantities of materials mobilised within a circular economy. Addressing this main challenge is critical because an ideal circular economy is currently hardly achievable due to diffusive and entropic effects. Narrowing the Loop reduces the pressure on the system and also ensures that not every practice in using plastics is welcome just because it is circular, for example by means of reuse or recycle.

The most radical way of Narrowing the Loop is to refuse plastic products by sufficiency of behaviour[79]. However, genuine sufficiency is difficult to achieve; it involves basic traits of frugality and asceticism. This would be conceivable at the level of the individual consumer, but at the level of the producer there is still a lack of incentives for operationalizing sufficiency. Therefore, refusing is more about substituting a product with a service or by offering the same function with a radical new product[77].

Often it is only about substituting the plastic with another material. In these cases, critical assessments are necessary to determine whether the alternative practice does not ultimately lead to more detrimental environmental impacts[80,81].

Smarter options, sometimes named 'rethinking', are to share plastic containing products (like cars or inflatable swimming pools) **or to design plastic products, so that they can be used sequentially or simultaneously in a multifunctional way** (e.g., polyurethane core in a sofa-bed, double ended pens, photochromic glasses). This is supported by the implementation of circular business models, such as sharing platforms and product-service-systems (PSS), as well as schemes that promote product redundancy and multifunctionality[82]. When designing for multifunctionality, the impact on total material consumption, service lifetime expectations etc. need to be carefully considered.

The most technical way to narrow the loop is to use the plastic more efficiently. This means realizing the same function with less material. In a study comparing plastic packaging in 1991 and 2013, German GVM showed that the amount of plastics could be reduced by more than 25% through technical improvements[83]. However, if efficiency is achieved by reinforcement (glass or carbon fibres) or multilayers (barrier packaging) one has to keep in mind rebound effects, such as limited recyclability at the end-of-life.

Narrowing the Loop is the most challenging approach, requiring the most radical transformation, but it also promises the highest impact. To refuse, rethink or reduce product use means to manufacture less or other products and to consume less material. Thus, the measures for narrowing the loop are expected to have extraordinary important effects on reaching the overarching goals. However, especially refuse and rethink need a cultural turn and radical new business models, which hardly can be realised in short term and for all plastics applications.

Currently, business models for refusing or reducing plastics are widely missing especially for plastics producers as they are focused on increasing production. Therefore, we need to focus on redesigning and implementing appropriate business models.

3.2.2 Operating the Loop – sustainable sourcing and avoidance of losses

Operating the Loop refers to using renewable energy for all processes and minimizing material losses along the plastics value circle as well as ensuring sustainable sourcing of feedstocks for plastics production.

The energy use in the plastics sector has to be fully decarbonised from the extraction of feedstocks to the production and recycling of plastics. Supplying renewable electricity and heat to the plastics sector could achieve substantial GHG emission reductions[4,5]. This effect could be increased by the electrification of process energy in chemical production, e.g., in steam crackers[84].

A major obstacle to a CPE is plastic loss during plastic production, use, recycling and end-of-life, which can have negative environmental impacts as plastic emissions to the environment (littering and microplastics, see Section 2.1). To reduce plastic emissions, littering must be drastically reduced through design innovation, cultural change and enforcement of existing legal instruments. Micro- and nano-plastic emissions can be reduced by improving the abrasion resistance of plastic products (tyres, facade paints, etc.) without using critical stabilisers. Other important points for losses are sorting and recycling installations. They should be optimized in operation and process design to avoid microplastics formation and to improve the yield of recycled materials. In environmentally open applications, where recovery of the plastic products would be cumbersome or in plastic applications where losses to the environment cannot be avoided, sufficient degradability under the given environmental conditions must be ensured or the application must be banned[85].

A fully circular plastics economy is impossible since there will always be material and/or quality losses along the value circle in production, use or any end-of-life-treatment. Additionally, plastic demand keeps growing, at least worldwide[4]. This means that the need for primary plastic production will remain. **To reduce fossil feedstock use, the future plastics sector must switch to alternative feedstocks as quickly as possible. Future plastics will rely on recycled plastics, biomass and CO_2.**

Using biomass as feedstock for plastics promises significant GHG emission reductions[4,5,64,86]. Moreover, bio-based plastics could even act as a carbon sink when kept sequestered in products[4,87]. However, biomass production negatively impacts water bodies and natural ecosystems through agricultural intensification, eutrophication particulate matter emissions as well as direct and indirect land-use change[88]. Hence, ensuring a sustainable biomass supply is paramount so that the advantages of biomass use outweigh its trade-offs.

Also, the capture of CO_2 emissions and their utilisation (CCU) is seen as a promising future pathway to supply the carbon feedstock for the chemicals and plastics sector[89,90,91]. A long-term assessment by Meys et al. sees potential for significant GHG reductions through CCS and CCU for plastics[64]. Applying CCS and CCU to biogenic CO_2 emissions could even increase the mitigation benefit. However, the commercialisation of CCU is inhibited by its high energy use and still inefficient catalysts[89]. Hence, the availability of cheap renewable electricity on large scale is a precondition for CCU to become an important factor in the future chemicals and plastics sector. Moreover, significant research efforts and investments are needed to bring CCU technologies towards commercialisation.

3.2.3 Slowing the Loop – keeping products in use

Measures to maintain products and their functions as long as possible, such as extending their useful lifetime through durability, reuse, repair, refurbishment, and remanufacturing, are essential for slowing resource loops during product use phase. However, the successful implementation of these inner loops can be complex and often requires significant changes in technology, product design, revenue models, and social institutions. Users play a crucial role in the success of these measures, as their decisions on how to obtain, use, and dispose the products determine whether they are irreversibly consumed or have the potential to further circulate[92,93]. Studies have shown that reusable and durable plastic products have the potential to reduce resource usage and environmental impacts if they are used frequently[36,94].

This potential was demonstrated in a case study on the remanufacturing of medical products showing that the more products are returned and remanufactured, the more resources and emissions are saved[95]. Therefore, it is important to increase understanding of users' daily lives and how they use, manage, and loop products in order to improve the effectiveness for the strategies of Slowing the Loop.

Actions to be taken to slow the plastic loops are the establishment of a right to repair for electronics and other products containing plastics. The right to repair refers to the concept of allowing (end) users, consumers as well as businesses, to repair products they own or providing services without any manufacturer or technical restrictions[96]. Repair (as well as refurbishment and remanufacturing) must be made as easy as possible. This includes the availability of spare parts, updates for software and physical tools needed. The right to repair is an exemplary action of what enables businesses and society to provide, and to use products as long as possible instead of disposing them once their function is impaired[96].

More radical changes are needed in the way we use and consume products to accelerate a high product integrity in use and slow the plastic loop. This also includes surrendering individuality and fast trend-related changes in consumer behaviour. A shift from selling to service-oriented business models, i.e., providing access to products and services, can enable reverse logistics: products remain in the companies' ownership and are returned to the retailer or manufacturer after their use.

3.2.4 Closing the Loop – preservation of material quality after their use

Design, collection, sorting and recycling of plastic products need to be optimized for the desired target applications and the lowest environmental impact, instead of adapting recycling to the existing waste streams. In general, all European countries have a more or less sophisticated waste management system. However, there still is a lot of room for improvement.

Governments should focus on holistic waste management: Extended Producer Responsibility (EPR) systems should not only guarantee that all plastics are collected but also that they can be recycled with the desired quality and lowest environmental impact. Product design, collection, sorting and recycling technology needs to be aligned and match the recyclate quality required for the respective target applications. Landfilling as well as incineration of plastics have to be replaced by recycling as quickly and comprehensively as possible. To close the loop, it is crucial to organize and connect all stakeholders in a circular value chain, including industry, government, research, NGOs etc. Moreover, integrated assessments of economic and environmental impacts through scenario modeling needs to support decision making and guide investments[97,98,99].

Presently, most recycling technologies are either connected to the preservation of materials with reduced quality (e.g., mechanical recycling of polyolefins) or to regaining virgin material quality with considerable material losses (e.g., chemical recycling of mixed plastics). Recycling should be optimized based on atom efficiency and application. Plastic waste collection and sorting must be adapted to foster such an optimization in the near future, instead of adapting recycling to the available, often mixed and impure, waste streams. This requires the combination of existing and innovative recycling technologies, including chemical recycling since it allows for maintaining the quality of the recycled materials. Artificial intelligence such as machine learning algorithms could be a promising tool for choosing optimal recycling pathways, taking into account a wide range of influencing factors such as origin, contamination level, or age of the plastic waste. Additionally, polymer and product design need to be adapted to support such an optimized recycling system.

3.2.5 Examples for bottled water and agriculture mulching

Table 1 shows possible operationalizations of the R- and O-Strategies for two very different examples - bottled water and agricultural mulching. Not every use case has an implementation variant for every R strategy. For example, Remanufacture and Refurbish do not seem to be obvious strategies in the selected examples. The O-strategies as cross-cutting strategies should be considered in principle.

	Bottled water	Mulching films
R0 - Refuse	Drink water direct from the tap.	Use biomass (bark, grass, mulching material), especially where foils would be penetrated by plants.
R1 - Rethink	Use a soda streamer.	Develop an indicator giving information on UV-protection status.
R2 – Reduce	Reduce the weight of bottle regardless of whether they are disposable or reusable.	Reduction of weight, foil thickness is possible, but it may lead to fast fragmentation in application.
R3 - Reuse	Use reusable PET-bottle in a pool including cleaning.	Thicker foils can be reused up to 8 years.
R4 - Repair **R5 - Remanufacture** **R6 - Refurbish**	Make soda streamers more repairable.	Develop a repair tape fully compatible with foil and application.
R7 - Repurpose	Use old bottles as building material.	
R8 - Recycle	Recycle PET bottles by mechanical or chemical recycling of PET-bottles.	Recycling is possible but requires extensive cleaning as the films are typically very dirty after agricultural use.
R9 - Recover	Residues from recycling should be incinerated with energy recovery.	Residues from recycling should be incinerated with energy recovery.
R10 - Remine	Collect already littered bottles from the shoreline.	Clean the farmers' yards and environment.
O1 - Renewable energy use	Use electrified processes over the whole life cycle, e.g. for production, transport and cleaning. Cleaning could be used for storage of fluctuating energy.	Use electrified processes. Use foils not only for mulching but also for cooling, heating of soil to increase productivity.
O2 - Minimize material losses	Charge a deposit on all bottles, regardless of whether they are disposable or reusable. Make sure that caps are permanently fixed to the bottle.	Use rather thick foils instead of fleece, ribbon fabric or thin films. Use certified biodegradable foils in cases where collecting the foils leads to larger environmental damages.
O3 - Renewable feedstock	Check suitability of bio-based polymers like PLA, PHA or PEF for the bottle material.	PLA containing films are common, they should be optimised for reuse/recycling.

Table 1. Two examples of how the R and O strategies can be operationalised.

3.3 Hierarchy and ranking of strategies

The main approaches described above including the respective R-Strategies can be structured according to Figure 6. Operating the Loop is an overarching approach that sets the preliminary conditions for a sustainable circular economy: the minimization of material losses, the switch to renewable resources to produce materials, and the provision of renewable energy for operating the circular economy. These – herein named O-Strategies, derived from operating strategies – should be applied independently from the chosen R-strategies.

	R-Strategies	Operating the loop: O-Strategies		
Narrowing the loop:	R0 - Refuse	O1 - Renewable energy use	O2 - Minimize material losses	O3 - Renewable feedstock
	R1 - Rethink			
	R2 - Reduce			
Slowing the loop:	R3 - Reuse			
	R4 - Repair			
	R5 - Remanufacture			
	R6 - Refurbish			
	R7 - Repurpose			
Closing the loop:	R8 - Recycle			
	R9 - Recover			
	R10 - Remine			

Figure 6. Main approaches, R-Strategies and O-Strategies to create a sustainable, circular economy.

The application of the O-Strategies requires no choice: All the three are to be used in parallel and as completely as possible. On the other hand, deciding on an appropriate R-strategy is a complex process. Typically, for a given application or service, more than one R-strategy is possible. The relevant strategies have to be carefully compared with each other regarding their feasibility and impacts (Figure 7). However, case-by-case assessments provide limited general guidance on the prioritization of strategies.

Therefore, a default-procedure for choosing a preferred R-Strategy is desirable, following the waste hierarchy. Deviations from this procedure should only be made if detailed consensual comparative environmental case studies clearly suggest otherwise. This proposal matches the procedure that is outlined in article 4 of the European Waste Framework Directive regarding the waste hierarchy. However, in practice following the waste hierarchy has not played an important role to date. Instead, different technologies, applications and business systems have been installed and operated without taking the higher levels of the waste hierarchy into account. For example, in the existing systems for packaging waste recycling in Germany, the license fees are determined based on recyclability. It is not relevant that the packaging could just as well have been realized as a re-use solution.

As scientists, we usually demand fundamental evidence with respect to the appropriateness of the chosen system, such as the waste hierarchy or the ranking of R-Strategies.

Potting and other authors have argued that the ranking results from expected lower negative environmental impacts at the respective higher level of the ranking[77]. However, a closer look at individual cases will reveal numerous deviations from this reasoning. Furthermore, the rankings will change depending on the analysed impact categories. It is conceivable, for example, that a reuse system is inferior to a recycled single-use system in terms of climate impact, but clearly superior in terms of plastic emissions and sovereignty.

A more viable argument for the waste hierarchy in our opinion is that each entry level ensures that the larger R-number remain as future options while every lower R-number becomes impossible: A thermally recovered (i. e. burnt) product or material (R9) can never be recycled again (R8); A recycled one (R8) cannot be reused (R3) anymore; One that is already reused or repaired (R3, R4) cannot be rethought (R2); And every product that is already in place (R2-R9) cannot be refused (R1) anymore. It becomes clear, that the entry into the R hierarchy should therefore take place at the lowest possible R-number.

From this simple but stringent interpretation, the application of the hierarchy seems to be sufficiently justifiable.

Based on these arguments, it would make sense for every plastic application to work through the R-Strategies' ranking from top to bottom and favour the first level that is feasible and appropriate. Nevertheless, the following levels have to be considered in the overall strategy. For example, a reusable product, should also be repairable and at the end-of-life it should be recycled, not incinerated. Finally, recover and remine are no entry strategies – they represent the old linear systems, however, they come into action when circulating is not possible anymore (Figure 7).

In cases of justified doubts of any stakeholder that the chosen entry level does not lead to the best performance in reaching the overarching goals, a case-by-case-study would have to be conducted to provide reasonable arguments for using a lower ranked R-Strategy. However, the basis for such a decision requires a balanced consideration of the various options, a critical approach to deal with uncertainties, and a mutual definition of the boundaries of the systems to be compared as well as the choice of parameters for comparison. Typically, an LCA will be carried out based on these definitions. Unfortunately, state of the art LCA mostly do not reflect impacts associated with plastic pollution or sovereignty. Furthermore, existing approaches to standardize LCA by so called product category rules (PCR) are limited to typical sector applications.

However, deciding on very different strategies corresponding to different levels in the ranking requires cross-sector agreements and boundary conditions for the evaluation process. Making a fair and robust comparison as a basis for switching from refuse to reuse or from reuse to recycle is anything but trivial and will take time. New and more holistic approaches and methodologies are needed to support and moderate such multistakeholder processes that decide on the choice of R- and O-strategies.

Working through the ranking and choosing the highest level possible should be fostered by regulation and/ or fiscal incentives. Furthermore, it should be incorporated into the educational canon of designers, engineers and business economists and it should form the base of corporate and sectoral organisational structures and business practices.

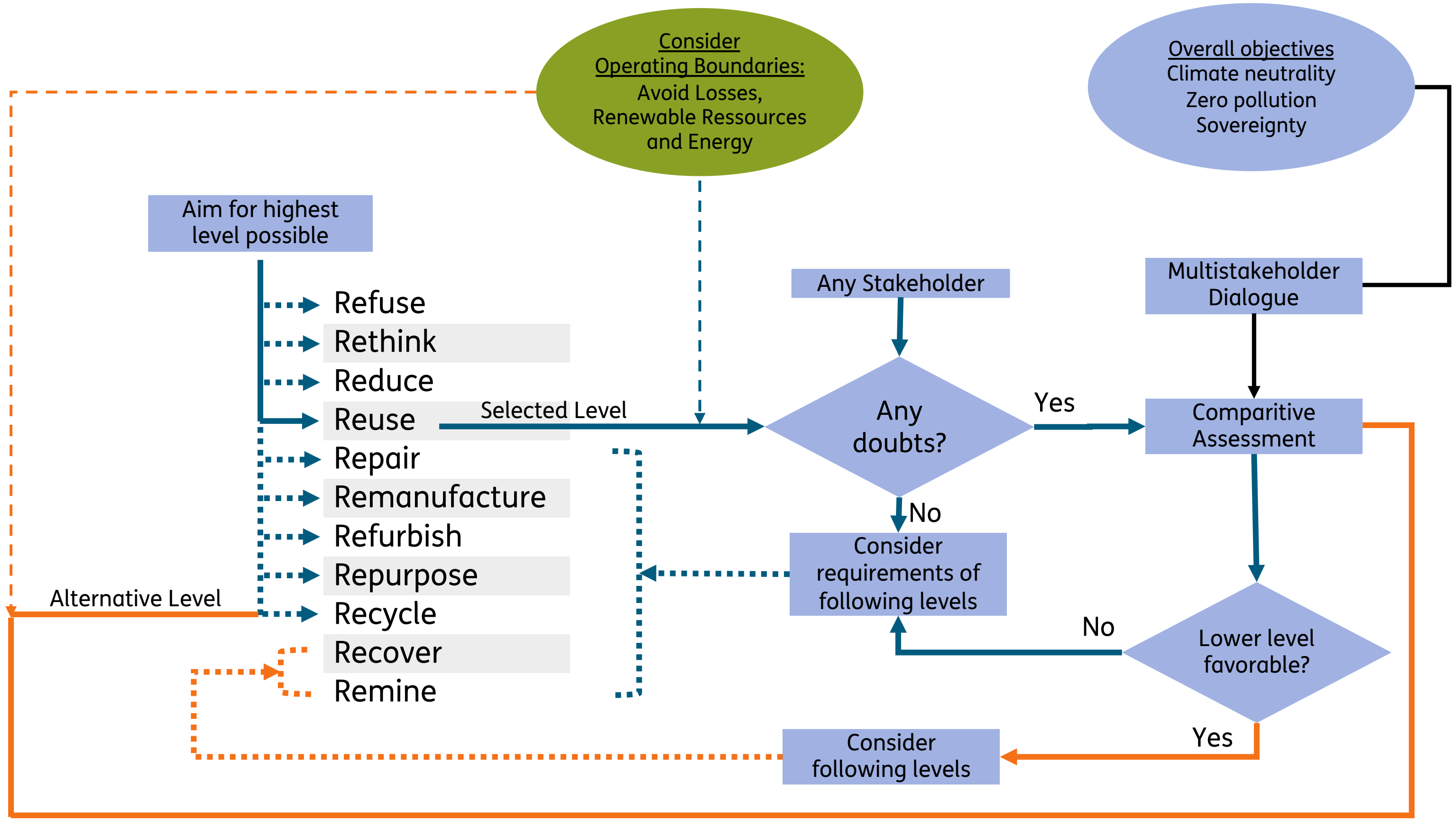


Figure 7. Hierarchic procedure of choosing the appropriate first R-strategy.

Figure 7 illustrates an example, in which the options reuse and recycle are to be compared. First, the higher ranked alternative 'Reuse' is to be evaluated. In case that no stakeholder expresses doubts about the preference of this option, it should be chosen. However, it must be guaranteed that the reuse system considers the requirements of the following levels and does not lead to any blockade. The latter might be the case if a multi-material design is chosen, which renders later recycling of a discarded reusable plastic product impossible.

Therefore, if any reasonable doubts about the efficiency of a reuse solution are expressed by any stakeholder, a detailed comparative assessment should be performed. It is inevitable in that situation that the assumptions and parameters of that assessment are agreed upon in a multistakeholder dialogue. Should the result indicate that the lower level, in this case recycling, is favourable, this option is to be chosen. Again, care must be taken not to compromise the following levels. That means in the given example, e.g., not to use halogenated polymers or additives which interfere with energetic utilization of rejected waste for recycling.

Stephan Kabasci likes the durability of plastics in his 16-year old computer monitor.

Chapter 4
Actions to be taken

Anna Schulte understanding the challenges of mixed plastic waste.

4.1 Transition to a sustainable, circular plastics economy

The increasing demand for circular plastics in high quality applications, such as food packaging, car parts or synthetic textiles needs a rapid and holistic change. This transition can only succeed if cross-sectoral collaboration including science, industry, politics and citizens is fostered. This requires a high commitment to transparency and openness to results as well as incentives for industry collaboration beyond the individual company and new and complementary technologies.

The X-curve framework (see Figure 8) can be used to describe the patterns and dynamics of structural societal change, when old systems are breaking down and new systems are emerging[100]. The transition from a linear, fossil-based economy to a circular, sustainable economy can be described in such a framework.

Currently, the existing fossil and linear system is destabilizing. Damages from climate change and plastic pollution are becoming more evident, and the lack of disposal capacities and supply bottlenecks are becoming increasingly obvious. The new circular, renewable system is already accelerating. Alternative technologies, such as chemical recycling, new reuse systems, or bio-based plastics, emerge, and stakeholders connect with each another.

However, the old system is far away from breaking down and the new one is still not visible in its final shape. Major uncertainties exist, pertaining to the phase-out of fossil fuel technologies and the emergence of new production technologies (e.g., biorefineries, crude to chemical) and feedstocks (e.g., biomass, CO_2). New, renewable plastic types will emerge that are not only optimized for their application but also for high quality recycling. The impact of such new plastic types on the current infrastructure of the value chain and their potential environmental impact is unknown.

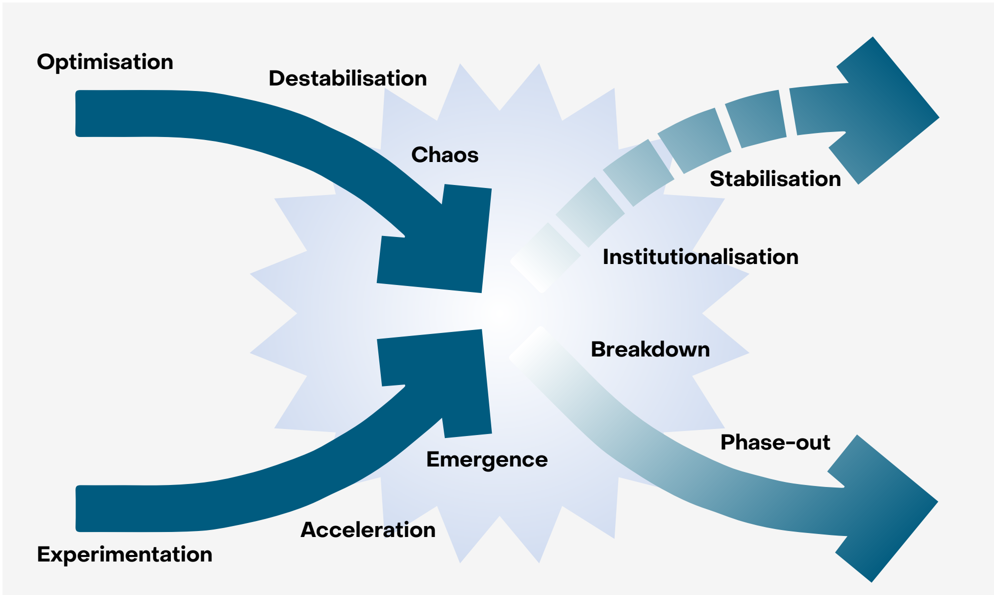


Figure 8. Dynamics of structural change (redrawn from[100]).

In addition, new chemical recycling technologies are under development and in the scale up phase. Moreover, the value chain needs to be reorganized to match the requirements of circular business models. The institutionalisation of the new system in form of new suitable regulations or organisations is still very fragmented. It is uncertain whether the transition can be conducted in a smooth and smart way or if temporarily economic, social and perhaps also ecological drawbacks are unavoidable.

When creating a circular plastic value chain, getting started is most difficult, because a circular value chain has no beginning and no end and stakeholders in the value chain are not used to working together. Furthermore, current consumption patterns, business models and logistics do not support the R- and O-Strategies. For example, sharing of products (rethink) requires a suitable infrastructure, questions of liability must be clarified and sometimes even a cultural turn is needed. Therefore, the transition to a sustainable, circular plastics economy implies several, partly quite drastic changes at different levels, and the following actions are quickly needed (Figure 9).

Legislation and policy

- Short-term perspective: Legislation should quickly strengthen the approach of closing the loop by restricting unrecyclable materials, obliging target amounts of application of recycled plastics in products and banning incineration and landfilling for plastics. Refuse, rethink and reuse should concurrently be promoted for lowering the total plastics material usage.
- Long-term perspective: Forthcoming regulations on plastics should be put in place promoting especially the principles of narrowing the loop (refuse, rethink, reduce), operating the loop (use of renewable resources and energy, minimising losses), and slowing the loop (reuse, repair etc.). The use of Design for Longevity and Design for Recycling principles must be obliged. These actions need to be implemented on short term as well to meet our long term goals.
- Internalise external costs and environmental impacts: Costs of environmental impacts have to be included in product prices. This makes plastics made from recycled material, biomass, or CO_2 more competitive to those made from virgin fossil feedstocks. New tools for assessing environmental impacts of plastics are needed. Especially plastic emissions (littering, microplastics) are not covered in today’s assessment tools (e.g., LCAs).

Circular chain cooperation

- Follow the extended waste hierarchy: Use the proposed default-procedure for choosing a preferential R-Strategy following the waste hierarchy from R0 to R9 as illustrated in Section 3.3. Deviations from this procedure should only be made if detailed consensual comparative environmental case studies clearly suggest otherwise. In any case, make use of the O-Strategies as completely as possible.
- Implement unconventional business models and risk management: While business models are still conceivable for rethink (sharing, multifunctionality) and reduce (efficiency), the challenge will remain to find solutions how to integrate refuse. Refuse is expected to be a powerful strategy, particularly when realized without substituting plastics by other materials (cf. Section 2.3). It should be made attractive for both consumers and entrepreneurs. The financial risks arising from the introduction of disruptive technologies, the establishment of new circuits for sharing materials and products, fluctuating commodity prices etc. must be fairly distributed.
- Change the value chain and behaviour: If reuse is applied in a broader context, pooling and repairing become more attractive business cases. However, the shift of capital and human resources away from the chemical industry to other players along the value circle has to be made economically and socially acceptable, which requires reasonable governance. Consumers need to change their behaviour by asking for – and finally choosing – the circular alternatives.
- Collaborate in the value circle: Stakeholders who are not used to cooperate with each other must start working together. New actors will appear and must be integrated. Operators of reuse pools need to team up with producers and recyclers, e.g., for innovative product designs. Chemical industry, e.g., will need to collaborate with recyclers and biomass suppliers to secure the supply of raw materials.

- Manage competition and interdependencies: Waste treatment options compete with each other. It must be ensured that the best option is chosen, especially because thermal recovery and, expected large scale chemical recycling need massive waste inputs and tie up a lot of capital. The future operation of installations that still have their value and purpose, such as the municipal waste incinerators (MWI) with energy recovery, needs to be considered. District heating e.g. is often connected to the MWIs.
- Reorganise and track the plastic flows and their quality: The new circular system will require a reorganization and tracking of the plastics flows and their quality throughout the economy to link the product and material flows to suitable reuse or recycling systems and the desired target applications.

Design and development

- Redesign of polymers: In a circular economy, plastics should be made solely from recycled material, biomass or CO_2. Polymers and their functionality need to be driven towards oxygen-rich(er) molecules for more efficient use of biomass or CO_2, as chemical removal of oxygen requires a lot of energy.
- Develop new recycling technologies: Current and future recycling technologies must be developed further to simultaneously increase the material recovery rate as well as the quality of the recycled plastics and to minimize losses. Collection and sorting systems must be included since their efficacy has a strong influence on the performance of mechanical and chemical recycling of plastics.
- Extend the useful lifetime of plastic products with strategies such as durability, reuse, repair, refurbishment, and remanufacturing.

Information and education

- Inform and educate all stakeholders. This is of utmost importance needed for all types of stakeholders like product designers, marketeers, buyers, citizens, investors etc. to make sustainable choices. The benefits of refuse and reuse must be made known above all. At the same time, a change to a culture of repair and longevity is required.

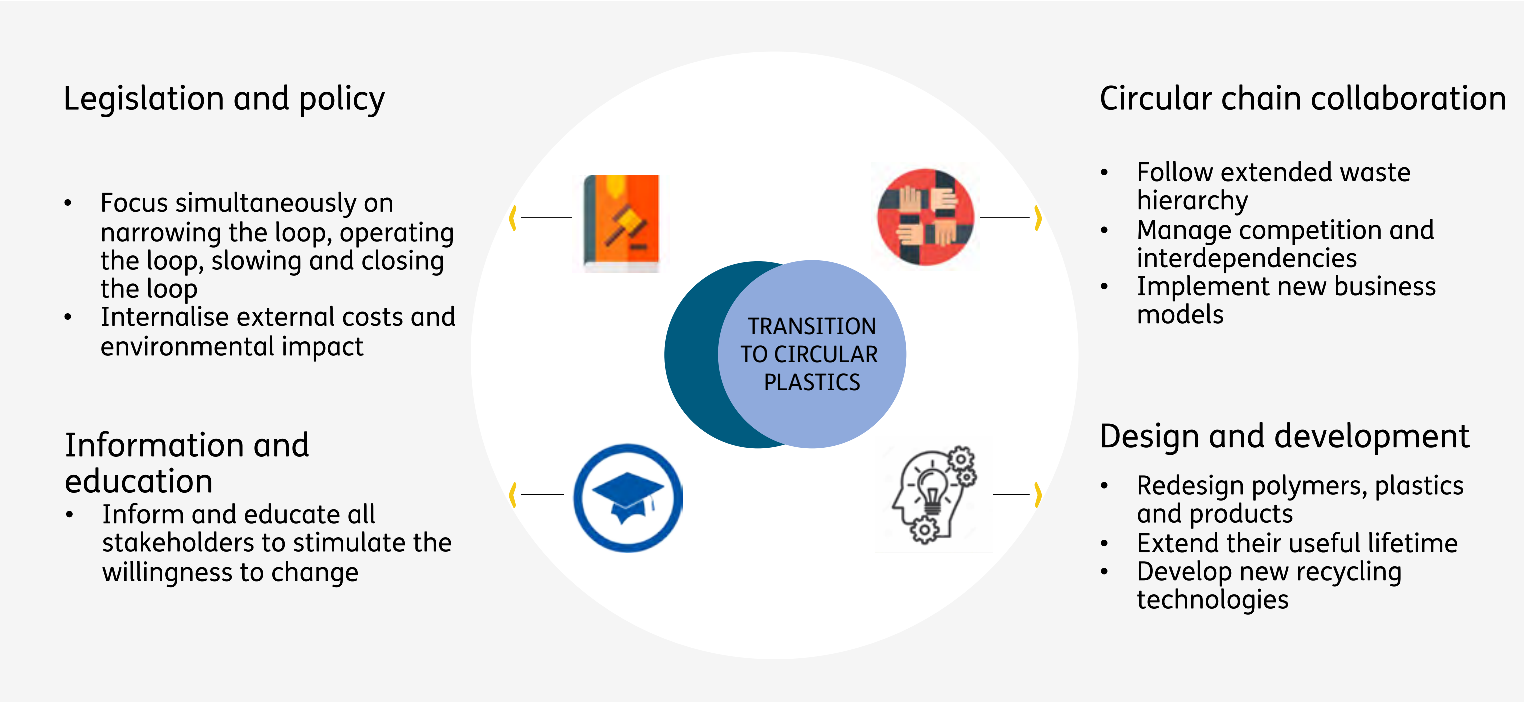


Figure 9. Actions needed for the circular plastics transition.

4.2 Actions for stakeholders

As pointed out in Section 4.1, this transition can only succeed if cross-sectoral collaboration including science, industry, politics and citizens is fostered. In this transition each stakeholder should take their responsibility.

Authorities

Legislation and policy are excellent drivers towards a circular transition. Authorities are responsible for measures, regulations and legislation. They should develop this in close collaboration with all stakeholders and be ambitious. Legislation based on emotions should be prevented. Legislative and policy measures should first limit market access for non-recyclable plastics. This will increase the pressure to develop plastic-free or recyclable solutions; in parallel, corresponding requirements in eco-design guidelines, environmental labels etc. should be strengthened. In addition, plastics that are recyclable should generally be excluded from thermal utilization. Increasing speed is essential. Following the ranking of the extended waste hierarchy and choosing the highest level possible should be fostered by regulation and/or fiscal incentives.

Companies (large & SME)

The total value chain has to collaborate to implement the principles of narrowing the loop (refuse, rethink, reduce), operating the loop (use of sustainable carbon, decreasing losses) and slowing the loop (reuse, repair). First, a (self-)commitment to a ranking of R-strategies seems reasonable here by industry, converters, producers, brand owners and retail. Solutions must be found for fair consensual multistakeholder life cycle analyses to identify the best strategy. Entrepreneurial solutions for the implementation of repair, refurbishment and remanufacturing must be found through cross-company cooperation, if necessary, supported by associations, taking into account a balance of interests between all players. In the area of design and development, new recycling technologies that can ensure a new quality of recyclates are urgently needed to ensure the recycling of both existing and future plastics. Mechanical and chemical recycling are complementary technologies that are both needed to close the circle. Existing collection and sorting system should be improved and adapted to future recycling technologies, as they have not yet led to the targeted recycling rates.

At the same time, solutions for reuse and durability must be developed and their degressive effects on material flows for recycling must be taken into account.

Schools, universities, NGO's & knowledge institutes

The actions on information and education have to be taken up by all types of stakeholders, from primary school to vocational schools and universities, NGOs, industry, knowledge institutes like TNO and Fraunhofer, partnerships etc. Misleading and confusing information should be prevented, and excellent communication of sustainable circular solutions is a must. In this way, citizens will be enabled to make sustainable choices. The training of designers, engineers and marketeers as key players for this change must be revolutionised. The focus must shift from the development of new products and manufacturing technologies to the use of the existing and their refurbishment.

4.3 What are TNO and Fraunhofer doing?

Fact-based and scientific research is needed to make sustainable decisions. As independent research institutes working in the field of plastics on both societal and technological research and innovation, we see TNO's and Fraunhofer's role is to inform all type of stakeholders about choices in the transition to circular plastics and to connect them, as well as a to be an adviser/prompter of the European Commission.

Based on our in-depth societal, economic and technological knowledge, we are able to set up strategies to give direction. We do this by developing a systemic model that describes the circular plastics ecosystem in terms of mass flows, unit operations, stakeholders, incentives, legislative frameworks, plastic quality, etc. We use this model as a basis for circular plastics transition scenarios and analyses, identifying weak spots in the value chain, technology, product & policy, for formulating 'reinforcement' actions (internal & external decision support) and managing of stakeholder processes.

TNO and Fraunhofer are also contribution to the transition by delivering circular plastics and products as well as the necessary process technologies to fill in gaps identified in the system analysis and not taken up by others. We evaluate new and competing technology options through in-depth environmental and social life cycle assessments.

Legislation and policy:
The EU adopted a European strategy for plastics in January 2018. It is part of the EU's circular economy action plan and builds on existing measures to reduce plastic waste. It is one of the main building blocks of the Green Deal. The EU is taking action to tackle plastic pollution and marine litter to accelerate the transition to a circular and resource-efficient plastics economy. Specific rules and targets apply to certain areas, including single-use plastics, plastic packaging, microplastics, and soon bio-based, biodegradable and compostable plastics.

TNO and Fraunhofer advise the European Commission via direct conversations with EC commissioners, input via our national governments, and via organisations such as Circular Plastic Alliance and European Plastics Pact. In addition, TNO and Fraunhofer develop technology needed to comply with (upcoming) regulations. For instance, we invest in efficient new recycling technology to deliver high quality recycled materials to be ready to meet the targets on recycled materials for the various product groups that are currently under discussion.

In the Netherlands, actions to reach our 2030 circular goals are presented in the National Plan Circular Economy.

Furthermore, the Dutch Program Circular Plastics NL (8 years program of 500 Million Euros) started by 1 Jan 2023, in which TNO in collaboration with other stakeholders defined the program line system integration. In this program line a transition scenario model is developed that includes environmental impact, costs, logistics, behaviour, design and processes etc, to show the impact of these actions. The National Circular Economy Strategy in Germany is under development. Fraunhofer UMSICHT is taking part in that process.

Information and education:
Fraunhofer and TNO contribute to information and education by providing independent models, e.g., for assessing the worldwide effects of plastics production and for determining the generation, dispersion and impact of microplastics. Both institutions publish the results of studies on life cycle assessments of plastic products and their researchers take part in standardization and certification committees dealing with circular economy and microplastics issues. Developments of new assessment methods for measuring the circularity potential of products and for evaluating the quality of recycled materials or plastics leakage to the environment in LCA calculations will help stakeholders in just evaluations of plastics production and use. As with this white paper, the institutes inform stakeholders throughout society about the necessity of quickly transforming to a circular economy, the need to keep plastics in use as a sustainable material and the forthcoming changes and tasks for everyone in this transition.

Fraunhofer and TNO intensify their connections to designers, e.g., to the Folkwang school of design in Essen, the University of Twente or the International Design Center IDZ in Berlin who organize the annual German ecodesign award. The goal is to foster holistic views on environmental and circularity aspects in product design of plastic parts with a strong focus on rethinking and reducing material use.

Circular chain cooperation:
These actions should be taken up by all stakeholders of the value chain in close collaboration as pointed out in Section 4.2. A good example is the Horizon Europe project SYSCHEMIQ that has the objective to make a step-change in the transition to a circular plastics economy applying a systemic approach, from collection to recycling for mixed waste plastics in the trilateral region (NL, BE, GER). With a total number of 20 partners, including TNO and Fraunhofer UMSICHT, the project intends to facilitate the systemic and circular transition in the region and unlock large amounts of these plastic waste streams as potential feedstock to replace virgin plastics. Another example is the Dutch Circular Plastics NL program which includes more than 200 stakeholders of the total value chain, in which TNO is actively participating.

Fraunhofer actively addresses industry along the plastics value chain and related stakeholders like environmental NGOs, consumer rights protection agencies and politics in debates about circular solutions like the use of bio-based plastics in packaging.

Researchers have developed a tool to visualise the interaction of multiple stakeholders in transfer processes (SHIA – stakeholder interaction analysis). With the focus on cooperation for making use of wastes as resources, not only for plastics but also for building materials, metals and other materials, Fraunhofer developed the concept of CIRCONOMY® Hubs. It is a new, agile instrument for cooperation on the basis of a shared mission and a reliable data space to contribute to the circular economy and to develop innovations for sovereign value cycles, climate neutrality, circularity and bioeconomy. TNO, for example, has developed a training programme 'Orchestrating Innovation' in collaboration with the Erasmus Centre for Entrepreneurship (ECE) and Rotterdam School of Management. It is based on the unique combination of TNO's hands-on experience and expertise in the field of orchestrating innovation and relevant new concepts in management and business administration, innovation and transition management. The goal is to help participants achieving a more effective impact in public-private partnerships regarding social issues.

Design and development:
These actions should be taken up by industry and knowledge organisation like TNO and Fraunhofer:

- Material design: TNO is active in the 'inverse design' of materials/polymers, aiming at achieving functional materials with multiple end-of-life options (recycling and/or biodegradability), preferably using biomass as feedstock. TNO uses the realm of Machine Learning for this purpose, to rapidly setup new structure-property-function relationships as the bridge between feedstock and desired specification for an application.
- Product design: Fraunhofer UMSICHT carries out classic product design studies with accompanying prospective life cycle assessments. Examples are children's seats or vehicle components made of plastic. The institute has a Makerspace in which rapid implementations are possible from plastic-based mock-ups to functional prototypes. In addition, interdisciplinary teams of designers, engineers and psychologists, building on the approaches of speculative design, are exploring unknown plastic worlds and design conceivable futures and radically new applications from plastic. interactions between plastic (product) and human, their beliefs and value attributions towards plastics are investigated and made usable by means of methods from empirical psychology to social research.
- Process Design: New process design is needed for sorting, pre-treatment and recycling. TNO is active in the development of pre-treatment technologies to remove undesired compounds in mechanical and/or chemical recycling as well as in recycling technologies. TNO and Fraunhofer work together in the development of new dissolution technology under superheated conditions to recycle ABS, brominated flame retardants and antimony trioxide from Waste Electrical and Electronic Equipment (WEEE) plastics. Furthermore, TNO developed the MILENA OLGA technology for thermochemical recycling of polyolefins to monomers. Finally, TNO works on new upcoming technologies such as catalytic depolymerisation of polyolefins and gasification.

Fraunhofer UMSICHT and TNO help in the decision making between systemically relevant process options in the area of chemical vs. mechanical recycling, reuse vs. single-use or repair vs. replace. For the decision between replacement and repair of plastic components after an accident or failure, Fraunhofer UMSICHT creates life cycle assessment-based decision tools. These are used, for example, in the processing of claims after motor vehicle accidents.

4.4 What is next?

There are numerous networks and many good studies on the Circular Economy. But as the German author Erich Kästner put it, “There is nothing good. Unless you do it.” (“Es gibt nichts Gutes. Außer man tut es.”). TNO and Fraunhofer UMSICHT have therefore decided to build a hands-on platform for plastics in a circular economy: European Circular Plastics Platform – CPP. It will give companies, associations and non-governmental organizations the opportunity to work together on existing barriers and promising solutions for a Circular Plastics Economy.

A particular goal of the platform is to connect companies along the circular pathways and develop new cross-company business models. This is imperative, as the previous gate-to-gate approach took insufficient account of the responsibility and opportunities for the upstream and downstream value chain. The platform also sees itself as a driving force for a technologically sovereign European plastics industry that is robust in the face of volatile markets and geopolitical crises. It brings environmentally critical aspects of plastics use to the table in order to jointly search for suitable solutions for the substitution of critical substances in plastics or for the avoidance of microplastics from plastics applications.

Specific examples include substitutes for per- and polyfluorinated additives or polymers, which play a central role in many high-tech applications, or alternatives to weathering facade paints or agricultural plastic films which are a main source of microplastics.

The platform will offer its members regular hands-on workshops on plastics topics, discussion panels on current issues, and participation in multi-client studies on pressing technical challenges. Regular meetings will be held in the cross-border region of Germany and The Netherlands as well as online.

References

1 Geyer, R., Jambeck, J. & Law, K. Production, Use, And Fate Of All Plastics Ever Made. Sci. Adv. 3, 25–29 (2017).
2 IEA (International Energy Agency). The future of petrochemicals - Towards more sustainable plastics and fertilisers. https://www.iea.org/reports/the-future-of-petrochemicals (2018).
3 World Economic Forum, Ellen MacArthur Foundation & McKinsey & Company. The new plastics economy: Rethinking the future of plastics. https://www.weforum.org/reports/the-new-plastics-economy-rethinking-the-future-of-plastics (2016).
4 Stegmann, P., Daioglou, V., Londo, M., van Vuuren, D. P. & Junginger, M. (2022). Plastic futures and their CO_2 emissions. Nature 612, 272-276 (2022). https://doi.org/10.1038/s41586-022-05422-5
5 Zheng, J. & Suh, S. Strategies to reduce the global carbon footprint of plastics. Nat. Clim. Chang. 9, 374–378 (2019). https://doi.org/10.1038/s41558-019-0459-z
6 Cabernard, L., Pfister, S., Oberschelp, C. & Hellweg, S. Growing environmental footprint of plastics driven by coal combustion. Nat Sustain 5, 139–148 (2022) https://doi.org/10.1038/s41893-021-00807-2.
7 Schwarz, A. E., Lensen, S. M. C., Langeveld, E., Parker, L. A. & Urbanus, J. H. Plastics in the global environment assessed through material flow analysis, degradation and environmental transportation. Sci. Total Environ. 875, 162644 (2023).
8 Chamas, A. et al. Degradation Rates of Plastics in the Environment. ACS Sustain. Chem. Eng. 8, 3494–3511 (2020).
9 Maga, D. et al. Methodology to address potential impacts of plastic emissions in life cycle assessment. The International Journal of Life Cycle Assessment, 27(3), 469-491 (2022).
10 Gall, S.C. and Thompson, R.C. The impact of debris on marine life. Marine pollution bulletin 92(1-2), 170–179 (2015).
11 Leslie, H.A. et al. Discovery and quantification of plastic particle pollution in human blood. Environ. Int. 163, 107199 (2022). https://doi.org/10.1016/J.ENVINT.2022.107199
12 Ragusa, A. et al. Raman Microspectroscopy Detection and Characterisation of Microplastics in Human Breastmilk. Polymers 14, 2700 (2022). https://doi.org/10.3390/POLYM14132700
13 WHO. Dietary and inhalation exposure to nano- and microplastic particles and potential implications for human health. (2022). https://www.who.int/publications/i/item/9789240054608.
14 Thiele, C. J. & Hudson, M. D. Uncertainty about the risks associated with microplastics among lay and topic - experienced respondents. Sci Rep 11, 7155 (2021). https://doi.org/10.1038/s41598-021-86569-5.
15 Rajput, A., Kumar, R., Gupta, A. & Gupta, S. Microplastics in the Air and Their Associated Health Impacts. in Plastic and Microplastic in the Environment (eds. Ahamad, A., Singh, P. & Tiwary, D.) 84–102 (Wiley, 2022). https://doi.org/10.1002/9781119800897.ch6.
16 Wright, S. L., & Kelly, F. J. Plastic and human health: a micro issue? Environmental science & technology 51(12), 6634–6647 (2017). https://doi.org/10.1021/acs.est.7b00423.
17 Levi, P. G. & Cullen, J. M. Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products. Environmental science & technology 52, 1725–1734 (2018).
18 European Commission. Study on the Critical Raw Materials for the EU 2023 – Final Report (2023) https://single-market-economy.ec.europa.eu/system/files/2023-03/Study%202023%20CRM%20Assessment.pdf.
19 Deetman, S. et al. Report on the current use of critical raw materials. (2017).
20 Andrady, A. L. & Neal, M. A. Applications and societal benefits of plastics. Philos. Trans. R. Soc. B Biol. Sci. 364, 1977–1984 (2009).
21 Millet, H. et al. The Nature of Plastics and Their Societal Usage. Issues Environ. Sci. Technol. 2019-January, 1–20 (2019).
22 Voulvoulis N. et al. Examining Material Evidence: The Carbon Fingerprint. https://www.imperial.ac.uk/media/imperial-college/faculty-of-natural-sciences/centre-for-environmental-policy/public/Veolia-Plastic-Whitepaper.pdf (2020).

23 Ashby, M. F. Materials and the Environment, Eco-informed Material Choice (3rd ed) (Butterworth-Heinemann, 2021).
24 DIN EN ISO 10456. Building materials and products –Hygrothermal properties –Tabulated design values and procedures for determining declared anddesign thermal values (2010).
25 Quested, T. et al. Helping people to reduce fresh-produce waste: Modelling the impact of selling products loose or in packaging. (WRAP, 2022). https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste.
26 Sasaki, Y., Orikasa, T., Nakamura, N., Hayashi, K. & Yasaka, Y. Lifecycle assessment of peach transportation considering trade - off between food loss and environmental impact. Int J Life Cycle Assess 26, 822–837 (2021). https://doi.org/10.1007/s11367-020-01832-7.
27 Quested, T. et al. Helping people to reduce fresh produce and dairy waste: The impact of packaging and refrigeration on shelf life. (WRAP, 2022). https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste.
28 Cox, J. et al. Helping people to reduce fresh produce and dairy waste: Citizen insights on the influence of packaging and date labels on disposal decisions. (WRAP, 2022).
29 Chou, M. C., & Wang, R. W. Y. Displayability: An assessment of differentiation design for the findability of bottle packaging. Displays, 33(3), 146–156 (2012).
30 Albrecht, S., Bertling, J., Fischer, M., Gehring, F., Kabasci, S., Prescher, T., & Schulte, A. Reusable Plastic Crates vs. Single-Use Cardboard Boxes (2022). https://doi.org/10.24406/publica-456.
31 Humbert, S. et al. Life cycle assessment of two baby food packaging alternatives: glass jars vs. plastic pots. Int J Life Cycle Assess 14, 95–106 (2009). https://doi.org/10.1007/s11367-008-0052-6.
32 Dhaliwal, H. et al. A life cycle assessment of packaging options for contrast media delivery: comparing polymer bottle vs. glass bottle. Int J Life Cycle Assess 19, 1965–1973 (2014). https://doi.org/10.1007/s11367-014-0795-1.
33 Ligthart, T.N. & Ansems, T.M.M. EnvPack, an LCA-based tool for environmental assessment of packaging chains: Part 2: influence of assessment method on ranking of alternatives. Int J Life Cycle Assess 24, 915–925 (2019). https://doi.org/10.1007/s11367-018-1531-z.
34 Gallego-Schmid, A., Mendoza, J. M. F., & Azapagic, A. Improving the environmental sustainability of reusable food containers in Europe. Science of The Total Environment 628, 979-989 (2018).
35 Ligthart, T.N. & Golkaram, M. Comparison of the environmental performance of one-way and refillable milk and wine packaging, TNO report,(2020).
36 Bertling, J., Dobers, K., Kabasci, S., & Schulte, A. Kunststoffbasierte Mehrwegsysteme in der Circular Economy - Eine Systemanalyse (2022). https://doi.org/10.24406/publica-11.
37 Häkkinen, T., Kuittinen, M. & Vares, S. Plastics in buildings. A study of Finnish blocks of flats and daycare centres. (2019).
38 Hajibabaei, M., Nazif, S. & Tavanaei, F. Life cycle assessment of pipes and piping process in drinking water distribution networks to reduce environmental impact. Sustain. Cities Soc. 43, 538–549 (2018).
39 Carlisle, S. & Friedlander, E. The influence of durability and recycling on life cycle impacts of window frame assemblies. Int J Life Cycle Assess 21 1645–1657 (2016). https://doi.org/10.1007/s11367-016-1093-x
40 Choi, Y., Ozaki, A. & Lee, H. Impact of Window Frames on Annual Energy Consumption of Residential Buildings and Its Contribution to CO_2 Emission Reductions at the City Scale. Energies 15, 3692 (2022).
41 Llantoy, N., Chàfer, M., & Cabeza, L. F. A comparative life cycle assessment (LCA) of different insulation materials for buildings in the continental Mediterranean climate. Energy Build. 225, 110323 (2020).

42 Zhao, J. R., Zheng, R., Tang, J., Sun, H. J., & Wang, J. A mini-review on building insulation materials from perspective of plastic pollution: Current issues and natural fibres as a possible solution. J. Hazard. Mater. 438, 129449 (2022).
43 Densley Tingley, D., Hathway, A., & Davison, B. An environmental impact comparison of external wall insulation types. Building and Environment 85, 182–189 (2015).
44 Dovjak, M. et al. Environmental impact of thermal insulations: How do natural insulation products differ from synthetic ones? IOP Conf. Ser. Earth Environ. Sci. 92, (2017).
45 Manan, S., Ullah, M. W., Ul-Islam, M., Atta, O. M., & Yang, G. Synthesis and applications of fungal mycelium-based advanced functional materials. Journal of Bioresources and Bioproducts 6(1), 1–10 (2021). https://doi.org/10.1016/j.jobab.2021.01.001.
46 Stelzer, L. et al. Life cycle assessment of fungal-based composite bricks. Sustainability 13, 1–17 (2021).
47 Livne, A., Wösten, H. A. B., Pearlmutter, D. & Gal, E. Fungal Mycelium Bio-Composite Acts as a CO_2-Sink Building Material with Low Embodied Energy. ACS Sustain. Chem. Eng. 10, 12099–12106 (2022). https://doi.org/10.1021/acssuschemeng.2c01314.
48 Sydor, M., Bonenberg, A., Doczekalska, B. & Cofta, G. Mycelium-Based Composites in Art, Architecture, and Interior Design: A Review. Polymers (Basel). 14, (2022).
49 Bertling, J., Dresen, B., Bertling, R., Aryan, V., & Weber, T. Artificial Turf Pitches - System Analysis for Switzerland and Germany (Fraunhofer UMSICHT, 2021). https://doi.org/10.24406/umsicht-n-640929.
50 Gallone, T. & Zeni-Guido, A. Closed-loop polypropylene, an opportunity for the automotive sector, Field Actions Science Reports 19, 48–53 (2019).
51 Duflou, J. R., De Moor, J., Verpoest, I. & Dewulf, W. Environmental impact analysis of composite use in car manufacturing. CIRP Ann. - Manuf. Technol. 58, 9–12 (2009).
52 Shanmugam, K. et al. Advanced High-Strength Steel and Carbon Fiber Reinforced Polymer Composite Body in White for Passenger Cars: Environmental Performance and Sustainable Return on Investment under Different Propulsion Modes. ACS Sustain. Chem. Eng. 7, 4951–4963 (2019). https://doi.org/10.1021/acssuschemeng.8b05588.
53 Wagner, S. et al. Tire wear particles in the aquatic environment - A review on generation, analysis, occurrence, fate and effects. Water Research 139, 83-100 (2018).
54 Unice, K.M. et al. Characterizing export of land-based microplastics to the estuary - Part I: Application of integrated geospatial microplastic transport models to assess tire and road wear particles in the Seine watershed. Science of the total environment 646, 1639-1649 (2019).
55 Williams, R.L. & Cadle, S.H. Environmental Degradation of Tire-Wear Particles. Rubber Chemistry and Technology 53 (4): 903–914 (1980).
56 Tian, Z. et al. A ubiquitous tire rubber–derived chemical induces acute mortality in coho salmon. Science 371, 185–189 (2020).
57 Bertling, J., Zimmermann, T., & Rödig, L. Kunststoffe in der Umwelt: Emissionen in landwirtschaftlich genutzte Böden (Fraunhofer UMSICHT, 2021). https://doi.org/10.24406/umsicht-n-633611.
58 Nußbaum, H. Biogassilage ohne Folie - lohnt das? Top Agrar (2007).
59 Uhl, A. et al. Entwicklung einer Siloabdeckung aus nachwachsenden Rohstoffen. Berichte aus dem TFZ 27 (2011). https://repository.publisso.de/resource/frl:6400504.
60 Joint Research Centre, Institute for Prospective Technological Studies, Beton, A. Cordella, M. Perwueltz, A. et al. Environmental improvement potential of textiles (IMPRO Textiles). (Publications Office of the European Union, 2014) https://data.europa.eu/doi/10.2791/52624.
61 van der Velden, N. M., Patel, M. K., & Vogtländer, J. G. LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. Int J Life Cycle Assessment 19(2), 331–356 (2014).
62 Bertling, J., Dau, K., Selig, U. & Werner, S. Releases of Microplastic into the Marine Environment - State of Knowledge and Options for Action. German Roundtable on Marine Litter (2022). https://muell-im-meer.de/sites/default/files/2022-03/Issuepaper_microplastics_final.pdf.

63 Urbanus, H. et al. Microplastics are everywhere: 70% reduction achievable https://publications.tno.nl/publication/34640142/ytwrjH/TNO-2022-microplastics-eng.pdf (TNO, 2022).
64 Meys, R. et al. Achieving net-zero greenhouse gas emission plastics by a circular carbon economy. Science (1979) 374, 71–76 (2021).
65 Wei, R. et al. Possibilities and limitations of biotechnological plastic degradation and recycling. Nat Catal 3, 867–871 (2020). https://doi.org/10.1038/s41929-020-00521-w.
66 Communication from the commission to the European parliament, the European council, the council, the European economic and social committee, the committee of the regions and the European investment bank: A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. COM 773 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0773 (2018).
67 Plastics strategy. https://environment.ec.europa.eu/strategy/plastics-strategy_en.
68 Reducing carbon emissions: EU targets and measures. https://www.europarl.europa.eu/news/en/headlines/society/20180305STO99003/reducing-carbon-emissions-eu-targets-and-measures.
69 Green Deal: key to a climate-neutral and sustainable EU. https://www.europarl.europa.eu/news/en/headlines/society/20200618STO81513/green-deal-key-to-a-climate-neutral-and-sustainable-eu.
70 Green Deal: New proposals to make sustainable products the norm and boost Europe's resource independence. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_2013.
71 Plastics Europe. Plastics - the Facts 2021. An analysis of European plastics production, demand and waste data. https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf (2021).
72 Crespi, F., Caravella, S., Menghini, M., & Salvatori, C. European Technological Sovereignty: An Emerging Framework for Policy Strategy. Inter Economics 56(6), 348-354 (2021).
73 Edler, J. et al. Technology sovereignty. From demand to concept. Perspektiven - Policy Briefs 02/2020 (Fraunhofer ISI, 2020) https://publica.fraunhofer.de/handle/publica/300409.
74 No time to waste: What plastics recycling could offer. https://www.mckinsey.com/industries/chemicals/our-insights/no-time-to-waste-what-plastics-recycling-could-offer.
75 Lansink, A. Challenging Changes – Connecting Waste Hierarchy and Circular Economy (LEA Nijmegen, 2017).
76 Waste Framework Directive. https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en.
77 Potting, J., Hekkert, M., Worrell, E. & Hanemaaijer, A. Circul ar economy: Measuring innovation in the product chain. (2017).
78 Monitoring Framework for the circular economy. https://commission.europa.eu/publications/monitoring-framework-circular-economy_en.
79 Jungell-Michelsson, J., & Heikkurinen, P. Sufficiency: A systematic literature review. Ecological Economics, 195, 107380 (2022).
80 Plastics and Sustainability: A Valuation of Environmental Benefits, Costs and Opportunities for Continuous Improvement. https://www.americanchemistry.com/better-policy-regulation/transportation-infrastructure/corporate-average-fuel-economy-cafe-emissions-compliance/resources/plastics-and-sustainability-a-valuation-of-environmental-benefits-costs-and-opportunities-for-continuous-improvement (2016).
81 Life Cycle Impacts of Plastic Packaging Compared to Substitutes in the United States and Canada. https://www.americanchemistry.com/better-policy-regulation/plastics/resources/life-cycle-impacts-of-plastic-packaging-compared-to-substitutes-in-the-united-states-and-canada (2018).
82 Moraga, G., Huysveld, S., Mathieux, F. et al. Circular economy indicators: What do they measure?. Resources, Conservation and Recycling 146, 452-461 (2019).
83 BKV. Entwicklung der Effizienz von Kunststoffverpackungen – 1991 bis 2013. https://www.bkv-gmbh.de/files/bkv-neu/studien/25271_LY_Folder_BKV_Effizienz_2016_v5.pdf.

84 Layritz, L. S. et al. The potential of direct steam cracker electrification and carbon capture & utilization via oxidative coupling of methane as decarbonization strategies for ethylene production. Applied Energy 296 (2021).
85 Bertling, J. Bertling, R. & Hamann, L. Kunststoffe in der Umwelt: Mikro- und Makroplastik (Fraunhofer UMSICHT, 2018) https://publica.fraunhofer.de/handle/publica/299055.
86 Spierling, S. et al. Bio-based plastics - A review of environmental, social and economic impact assessments. Journal of Cleaner Production 185, 476–491 (2018).
87 de Oliveira, C. C. N. Zotin, M. Z. Rochedo, P. R. R. & Szklo, A. Achieving negative emissions in plastics life cycles through the conversion of biomass feedstock. Biofuels, Bioproducts and Biorefining 15, 430–453 (2020) https://doi.org/10.1002/bbb.2165.
88 Pfau, S., Hagens, J., Dankbaar, B., & Smits, A. Visions of Sustainability in Bioeconomy Research. Sustainability (Basel, Switzerland), 6(3), 1222-1249 (2014).
89 Pires, L. et al. Capture and Reuse of Carbon Dioxide (CO_2) for a Plastics Circular Economy: A Review. Processes 9 (759) (2021).
90 Carus, M. & Raschka, A. Renewable Carbon is Key to a Sustainable and Future-Oriented Chemical Industry. nova-Paper #10 https://renewable-carbon.eu/publications/product/nova-paper-10-renewable-carbon-is-key-to-a-sustainable-and-future-oriented-chemical-industry-%e2%88%92-full-version/ (2018).
91 Bazzanella, A. M. & Ausfelder, F. Low carbon energy and feedstock for the European chemical industry https://cefic.org/app/uploads/2019/01/Low-carbon-energy-and-feedstock-for-the-chemical-industry-DECHEMA_Report-energy_climate.pdf (DECHEMA e. V. 2017).
92 Gallaud, D., & Laperche, B. Circular economy, industrial ecology and short supply chain (John Wiley & Sons, 2016).
93 Selvefors, A., Rexfelt, O., Renström, S., & Strömberg, H. Use to use – A user perspective on product circularity. Journal of cleaner production 223, 1014-1028 (2019).
94 Coelho, P. M., Corona, B., ten Klooster, R., Worrell, E. Sustainability of reusable packaging – Current situation and trends. Resources, Conservation & Recycling: X 6, 100037 (2020).
95 Schulte, A., Maga, D., & Thonemann, N. Combining life cycle assessment and circularity assessment to analyze environmental impacts of the medical remanufacturing of electrophysiology catheters. Sustainability 13(2), 898 (2021).
96 Right to repair. https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698869/EPRS_BRI(2022)698869_EN.pdf.
97 Wijngaard, M. et al. Don't waste it! Solving the dark side of today's plastic. White paper https://www.tno.nl/en/newsroom/2020/11/roadmap-circular-plastics-2050/ (TNO, 2020).
98 SYSTEMIQ. ReShaping Plastics: Pathways to a Circular, Climate Neutral Plastics System in Europe. https://plasticseurope.org/knowledge-hub/systemiq-reshaping-plastics/ (2022).
99 Schwarz, A. E. et al. Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. Waste Management 121, 331–342 (2021).
100 Hebinck, A. et al. An actionable understanding of societal transitions: The X-curve framework. Sustainability Science 17(3), 1009-1021 (2022).

Authors

TNO innovation for life

Dr. Esther van den Beuken
Dr. Jan Harm Urbanus
Dr. Paul Stegmann
Toon van Harmelen MSc
Dr. Tom Ligthart

Fraunhofer UMSICHT

Dipl.-Ing. Jürgen Bertling
Dr.-Ing. Stephan Kabasci
Anna Schulte MSc

Coordinators

Dr. Esther van den Beuken

Prof. Dr.-Ing. Manfred Renner

Contact

Dr. Esther van den Beuken
Principal Consultant Circular Plastics

esther.vandenbeuken@tno.nl

+31 6 2242 8547

linkedin.com/in/esther-van-den-beuken

Dr.-Ing. Stephan Kabasci
Strategic Project Development Circular Economy

stephan.kabasci@umsicht.fraunhofer.de

+49 208 8598 1164

linkedin.com/in/stephan-kabasci-88525477

tno.nl/plastics

umsicht.fraunhofer.de